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A Survey of Mining Associated Rockbursts

JANET C. JOHNSTON



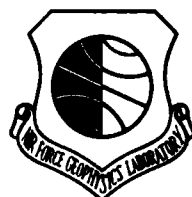
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drops result. It is possible that an inactive fault can be activated by the presence of a mine, resulting in Type II rockbursts. The search for reliable precursory phenomena has been basically unsuccessful. The upper limit for Type I events seems to be controlled by the strength of the rock, whereas the upper limit for Type II events is a completely open question at this time.

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Preface

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A Survey of Mining Associated Rockbursts

1. INTRODUCTION

Rockbursts, seismic events associated with mining, can be a significant part of seismicity in an area. In South Africa, for example, mining-induced seismicity is four orders of magnitude higher than background seismicity.

From both a scientific and a safety viewpoint, it is important to understand rockbursts in a generic sense: their mechanisms and the effects of mining on their number and magnitude. Better understanding of rockbursts will allow temporal and spatial prediction, and eventually lead to a reduction of their size and number.

The existing literature on rockbursts is incomplete and difficult to use. It largely consists of studies of individual localities, without comparison to other areas. Most of these studies do not present complete information. The scales by which magnitudes of events are measured are often inconsistent.

This thesis presents a summary of the available information from mines all over the world, in a variety of tectonic and geologic settings. The format makes existing data easier to compare and emphasizes gaps in the data. Where possible, the section for each area includes information on the geology, the mining operation, and seismic occurrences. There is considerable information on mines in Europe, North America, and South Africa, from which many detailed studies are available, but there is less information on other areas.

This thesis also presents possible explanations for some phenomena and makes recommendations for future studies.

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2. CHARACTERISTICS OF EARTHQUAKES AND ROCKBURSTS

Rockbursts and earthquakes share many characteristics. Rockbursts are caused by both natural factors, such as those that cause earthquakes, and artificial factors such as mining. Therefore, the terminology used to describe natural seismic events will be used in this thesis. This section provides an overview of this terminology as well as the characteristics of earthquakes and rockbursts.

The distinction between "naturally" occurring seismicity and induced seismicity must be understood when considering rockbursts and earthquakes. More than 90 percent of natural seismic events occur at plate tectonic boundaries. These events are associated with the mechanical movement of one plate against another (convergence, divergence, or sliding by). Intraplate earthquakes occur on faults also, but their cause (source of stress) is not always understood. Some possible mechanisms include glacial rebound, stress concentrations resulting from ancient magma intrusions, tidal loadings, presence of magma bodies, and volcanic activity.

Natural earthquakes often follow a pattern of foreshocks, mainshock, aftershocks, in which aftershocks tend to be much smaller than the main shocks, with at least one magnitude decrement from the main shock to the largest aftershock in the series (Bath¹). Not all natural earthquakes follow this pattern. Some mechanisms such as the movement of magma (see discussion of microseismicity in Socorro, New Mexico²) create activity in the form of shallow swarms. These swarms tend to have a very flat magnitude distribution.

Induced seismicity classically includes reservoir loading and rockbursts. In the first category, the increase of water pressure in the rock fractures and the additional load of the water can produce seismicity where none previously existed. (For an example of water reservoir loading, see LeBlanc and Engin.³) In the case of rockbursts, fairly large events (magnitudes in 3 to 4 range) can result from mining operations. A preexisting stress field favoring earthquake generation may be necessary for earthquake energy to be released by the presence of the mine, although in some cases there is evidence to the contrary (Dmowska, 1987, personal communication).

For both earthquakes and rockbursts, the terms hypocenter (or focus) and epicenter are used. The hypocenter refers to the latitude, longitude, and depth coordinates. The epicenter is the surface projection of the hypocenter, and gives no information on depth.

2.1 Characteristics of Earthquakes

Most information on earthquake phenomena comes from seismogram recordings. These are velocity versus time records made on velocity transducers, often in three dimensions: two horizontal and one vertical.

-
1. Bath, M. (1984) Rockburst Seismology, in Gay, N.C., and Wainwright, E.N. (Eds.), 1984, *Rockbursts and Seismicity In Mines*, South African Institute of Mining and Metallurgy, Symposium No. 6, pp. 7-16.
 2. Johnston, J.C. (1983) *Seismic Hazard Study for Selected Sites in New Mexico and Nevada*, AFGL-TR-84-0005, AD A143392.
 3. LeBlanc, G. and Engin, F. (1978) Induced seismicity at the Manic 3 Reservoir, Quebec, *Bull. Seism. Soc. Am.* **68**:1469-1485.

Medium to large earthquakes (magnitude 5.0 and above) can be recorded at regional to teleseismic distances by standardized stations. Smaller events and microearthquakes are best recorded by local networks or arrays.

2.1.1 SIZE MEASUREMENTS OF EARTHQUAKES

The most common measurements of the size of earthquakes are intensity, magnitude, and moment.

Maximum intensity is the least quantitative and involves an estimate of the damage caused by the event near its epicenter. It is derived from the Modified Mercalli Intensity scale, often abbreviated MMI, which ranges from I (not felt) to 12 (complete destruction).

Magnitude is usually a measure of the amplitude of shaking at some frequency normalized to a distance correction factor. Most common magnitudes quoted are m_b , body wave (1sec) magnitude; M_s , surface wave (20 sec) magnitude; or M_L , local magnitude.

To compute m_b , the relationship $m_b = \log A/T + D(d,z)$ is used where A is the amplitude of ground motion on the seismogram at approximately 1 sec, T is the period (1 sec) and $D(d,z)$ is the standard attenuation factor for distance and depth. See Johnston and Battis⁴ for a discussion of differences between magnitude scales.

Another type of magnitude, coda magnitude, is used in some localities such as New England, where magnitudes are small. It is based on the observation that for a given size of earthquake, the length of time that it takes for a seismogram to reach some fraction of its maximum height appears to be a constant.

Moment (M_0) is more closely related to the physical size of an earthquake than are intensity and magnitude, but is more difficult to compute since it requires an amplitude spectrum of the seismogram. It is therefore less readily available. Seismic moment is defined as $M_0 = \mu DS$ where μ is the rigidity modulus, D is the average slip, and S is the fault plane area. The moment is determined from the seismic spectrum, which generally is flat up to a "corner frequency" (Figure 1) at which point the spectrum drops off according to a function of the frequency⁵. The position of the corner frequency is a function of the physical dimensions of the rupture area of the fault, analogous in some ways to an antenna. The corner frequency moves to longer periods for larger earthquakes.

2.1.2 VALUES OF EARTHQUAKES

Earthquakes within a specific tectonic regime generally follow a linear relationship:

$$\log N = a - b M \quad (1)$$

where N is the number of earthquakes in magnitude interval $M \pm \Delta M$, a is the intercept corresponding to the level of seismicity, and b is the slope of the curve (Figure 2). The b -value is particularly

4. Johnston, J.C. and Battis, J.C. (1985) *Geokinetiks, Handbook of Geophysics and the Space Environment*, Jursa, A.S. (Ed.), Air Force Geophysics Laboratory, Hanscom AFB, MA.

5. Brune, J.N. (1970) Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.* **76**:5002.

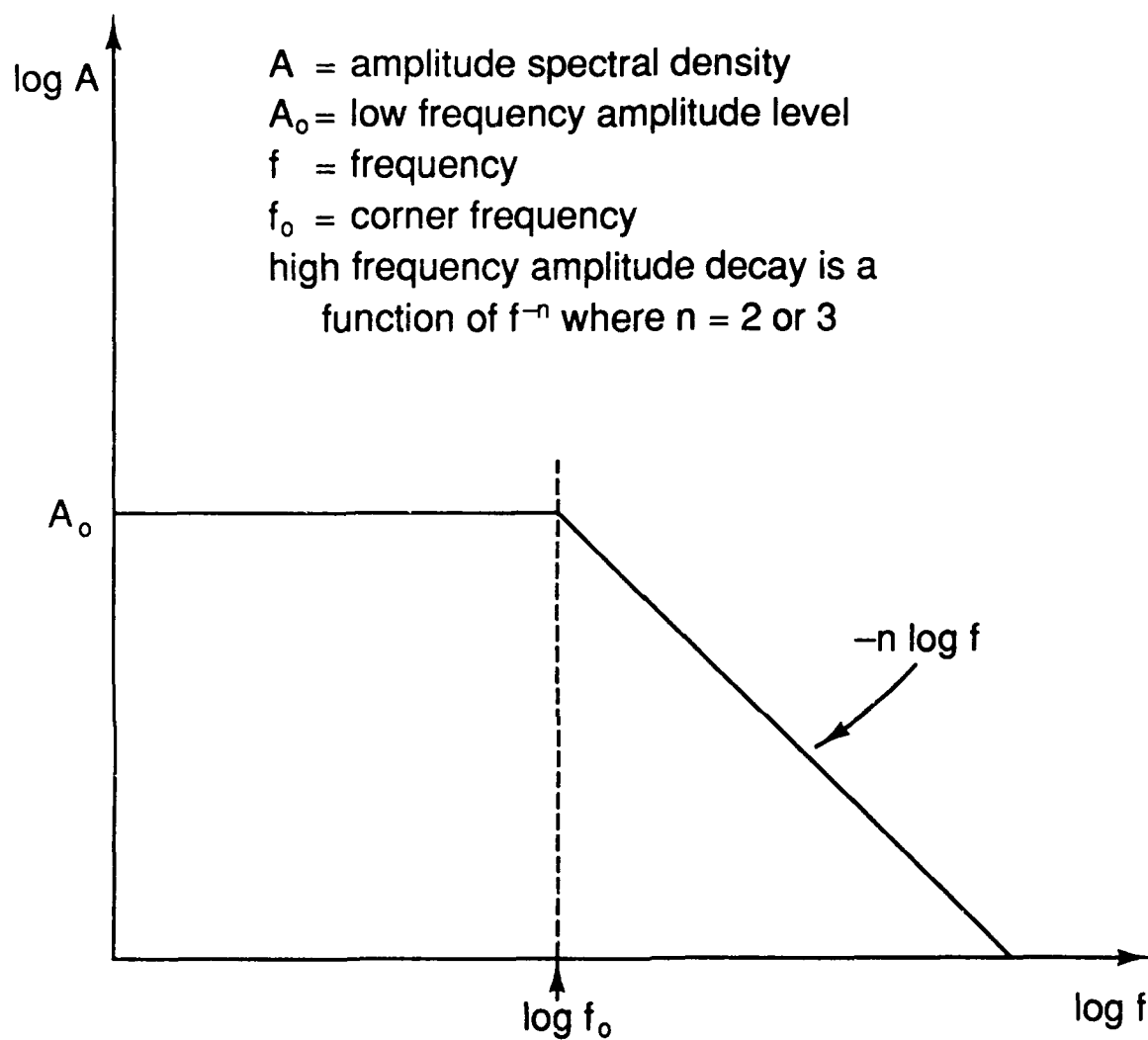


Figure 1. Generic far-field seismic spectrum.

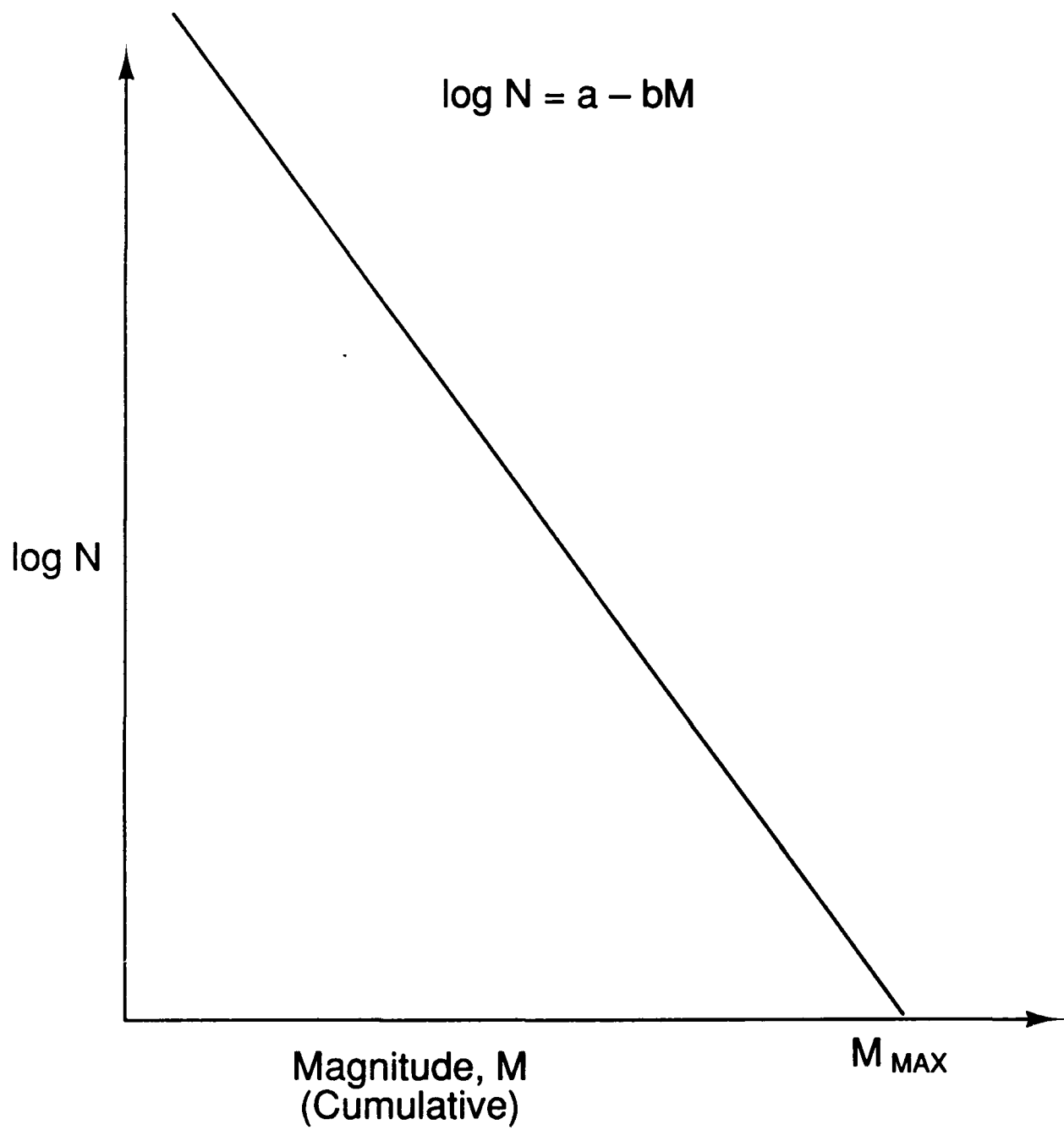


Figure 2. Generic magnitude-frequency curve.

significant because it is considered to be an indicator of the stress level. The b-values in different tectonic regimes and geologies are different. They tend to cluster around 1 ± 0.3 .

2.1.3 EARTHQUAKES, STRESSFIELD, AND FOCAL MECHANISMS

The focal mechanisms of naturally occurring earthquakes are usually pure double couple shear, that is, volume conservative sliding of one fault plane against another. Mechanisms include compressional thrust faulting, extensional normal faulting, and strike slip (see Johnston et al.,⁴). The orientation of the fault movement is on average aligned with the direction of the regional tectonic stressfield.

The type of mechanism and the orientation of the fault planes can be determined by the radiation pattern as expressed by the first motion polarity on a distribution of seismic recordings. When data are too sparse to define a solution for one event, a composite solution is often computed, which assumes that all events close in space have a common mechanism.

There are two important exceptions to the pure shear mechanisms. One is explosive sources, which are symmetric in cavity expansion. The other is rockbursts, some of which exhibit a 10 to 13 percent cavity collapse, non-shear component.⁶

2.2 General Characteristics of Rockbursts

The problem of damage and loss of life resulting from mining associated rockbursts is world wide. There have been many studies, such as the joint Polish-Czechoslovakian project (Section 4.1), but there are few that compare one area to another in different parts of the world.

Most information on rockbursts comes from small arrays of instruments installed by mining companies for the purpose of locating weak areas and warning of large seismic events. In a few locations, sophisticated three-component digital networks have been installed, but in most areas the instruments are less sophisticated and detailed analyses of waveform data are not routinely performed.

For the sake of clarity, the terminology in this study will follow the breakdown by Cook⁷: Rockbursts are violent failures of rock that cause damage to excavations. Bumps are violent failures of rock of seismic significance that do not cause damage. Rockfalls are collapses of loosened rock to the floor of a mine. Outbursts are rapid releases of absorbed or entrapped gas as a result of rock pressure. Outbursts are a major problem in Australia (Section 4.7).

Rockbursts that can be directly associated with mining rates are called Type I. There are also seismic events thought to be caused by the presence of the mine that may not occur in the immediate area of excavation; these are called Type II rockbursts. They involve slippage on preexisting faults.

6. Rudajev, V., Teisseyre, R., Kozak, J., and Sileny, J. (1986) Possible Mechanism of Rockbursts in Coal Mines, *PAGEOPH*, Vol. 124, Nos. 4/5.

7. Cook, N.G.W. (1976) Seismicity Associated With Mining, *Eng. Geol.*, Vol. 10, pp. 99-122. Cummins, A.B., Given, I.A. (Eds.), 1973, *SME Mining Engineering Handbook*, Vol. I, Soc. of Mining Eng. of the American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, NY.

Type II rockbursts are often larger than those more directly connected to the mining operation, the Type I events.⁸ Because of the existence of these larger Type II rockbursts, the distinction between natural and induced events can become fuzzy in the analysis of rockbursts. The division of rockbursts into Type I and Type II is shown in Table 1.

Table 1. Characteristics of Rockbursts

TYPE I	TYPE II
GENERALLY, RATE IS A FUNCTION OF MINING ACTIVITY	NOT ENOUGH DATA TO DETERMINE RELATIONSHIP WITH MINING RATES.
LOCATION IS GENERALLY WITHIN 100 m OF MINING FACE OR ON SOME PREEXISTING ZONE OF WEAKNESS OR GEOLOGICAL DISCONTINUITY NEAR THE MINE.	LOCATION IS ON SOME PREEXISTING FAULT SURFACE THAT MAY BE UP TO 3 km FROM THE MINE.
INTACT ROCK CAN BE BROKEN IN THE RUPTURE WHEN MINING INDUCED STRESSES EXCEED THE SHEAR STRENGTH OF THE MATERIAL. ORIENTATIONS OF RUPTURE PLANES CAN VARY.	ALL OCCUR IN PREEXISTING, POSSIBLY PRESTRESSED TECTONIC FAULTS. MINING MAY SIMPLY "TRIGGER" THESE EVENTS ON FAULTS OF PREFERRED ORIENTATIONS.
OFTEN HIGH STRESS DROPS OBSERVED.	STRESS DROPS MORE SIMILAR TO NATURAL EARTHQUAKES.
LOW TO MEDIUM MAGNITUDES.	POTENTIAL FOR HIGH MAGNITUDES.

That many rockbursts are stimulated by mining operations has long been accepted. Figure 3, modified from Cook⁷, shows a plot of numbers of rockbursts versus mining activity for the period 1913 through 1938 for a mining district in Czechoslovakia. From this figure it is clear that the rate of rockbursts was roughly proportional to the intensity of mining activity. Indeed, when an excavation is made, the potential energy of the system is changed by the product of the weight of the rock mined and its elevation. It has been shown⁹ that at most one-half of the change in potential energy can be stored as elastic strain energy (that is, stress concentrations) and that the rest must be released. One possible channel for this energy release is rockbursts. Plots similar to Figure 3 for other areas often show the same proportional relationship for rate-of-mining versus number of Type I rockbursts (see South Africa, Section 4.3; Ruhr Valley, Section 4.6).

8. Siller, H., Hurtig, E., Grosser, H., and Knoll, P. (1983) On the Nature of Mining Tremors, *Earthq. Predict. Res.* 2, pp. 57-63.

9. Jaeger, J.C. and Cook, N.W.G. (1969) *Fundamentals of Rock Mechanics*, Methuen, London.

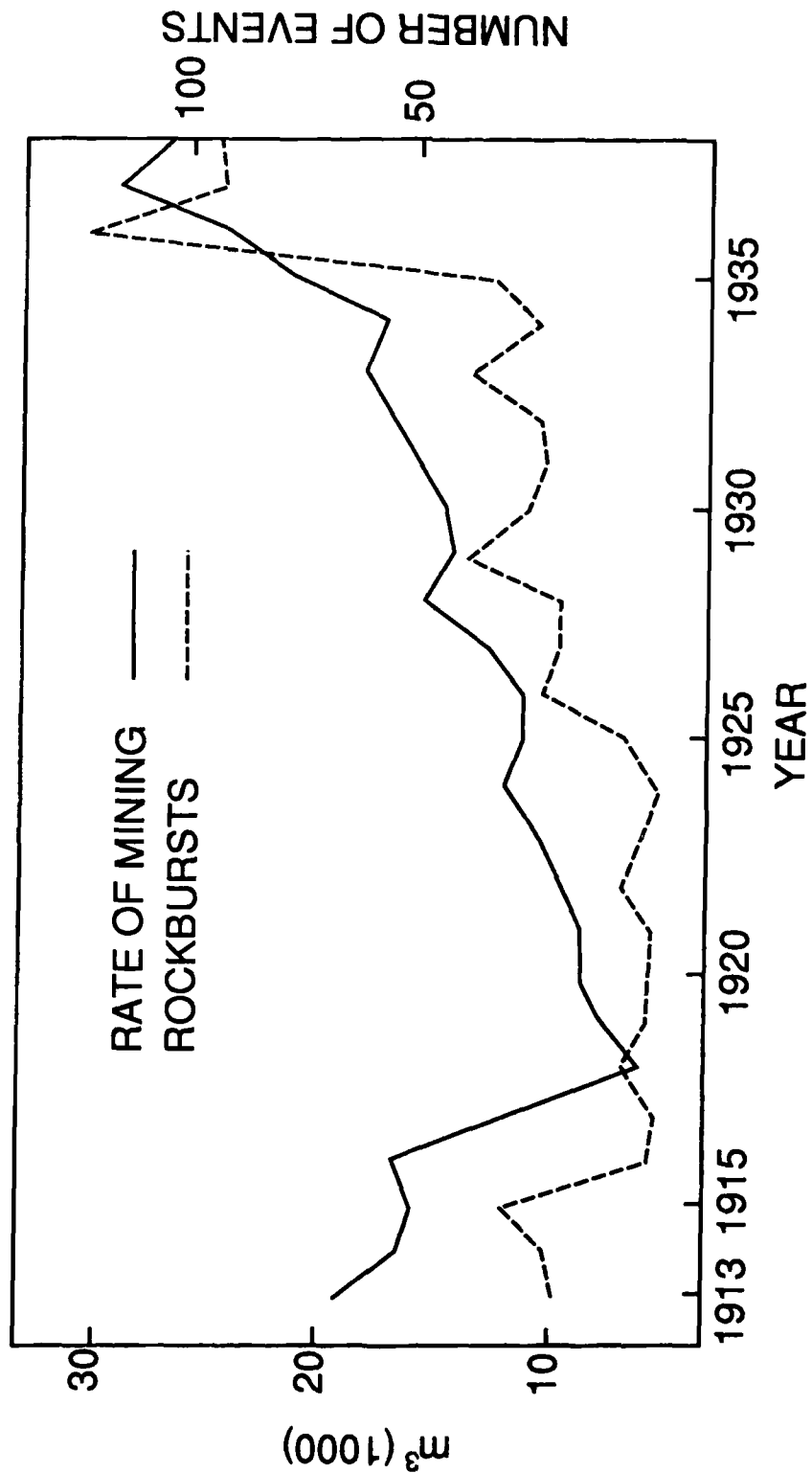


Figure 3. Rockbursts versus mining excavation rate (modified from Cook 1976).⁷
Curves are plotted for mining district in Czechoslovakia.

2.3 Detailed Characteristics of Rockbursts

This section presents the available information on the seismic characteristics of rockbursts. Because of the similarities between earthquakes and rockbursts, the same terminology is used.

2.3.1 SIZE MEASUREMENTS OF ROCKBURSTS

Since rockbursts generate motion similar to earthquakes, the same measurement scales are generally applied to them: intensity, magnitude, and moment.

Magnitude reports from different study areas are difficult to compare for two reasons:

(1) Reported results often do not specify the type of magnitude quoted; (2) Magnitudes are often calculated on a local scale normalized to some local event, so magnitudes from one area are meaningful relative to each other but may differ by a constant from magnitudes reported from other areas. Other size measurements, such as intensity and moment, are not generally reported.

2.3.2 b-VALUES OF ROCKBURSTS

The variations in the b-value in the magnitude-frequency relationship, $\log N = a - bM$ (Equation 1), are considered to be an indicator of the state of stress in the geologic formation.¹⁰ In some regions, lower b-values have been observed before the occurrence of very large seismic events, so possibly the low b-values can be associated with a higher stress state before an impending event. In fact, Gibowicz¹¹ found that in two cases in Poland where long wall mining was performed, b-values for tremors occurring ahead of the face were significantly lower than for tremors behind the face. This is for a sample of over 200 tremors, most of which occurred ahead of the face. The b-values oscillated in time and five of the largest events occurred during the lowest b-value intervals.

McGarr (personal communication) noted that when the excavation rate is cut in half in the South African mines, the seismicity is proportionally reduced; however, the b-value remains constant. From the discussion in Section 2.1.2, this implies that the level of the stressfield does not change with the change in level of activity.

2.3.3 ROCKBURSTS, STRESSFIELD, AND FOCAL MECHANISMS

Several researchers have attempted to relate rockburst focal mechanisms to the regional tectonic stressfield. Most find a relationship to the presumed tectonic stressfield, but mine geometry and the orientation of local fractures may also be important factors.

Gibowicz (many papers) studied the four largest rockbursts (magnitudes 4.1 to 4.6) in Poland (Belchatow and Byton coal mines and Lubin Copper) and concluded that the fault mechanism was shear slip with orientation consistent with the local tectonic stressfield. Here the stressfield that initiated the bursts had a tectonic component exceeding that of the mining induced rockbursts. Thus,

10. Dmowska, R. (1984) *Rockbursts and Seismicity in Mines*, South African Institute of Mining and Metallurgy, Symposium No. 6, p. 63.

11. Gibowicz, S.J. (1979) Space and Time Variations of the Frequency-Magnitude Relation for Many Tremors in the Szombiorki Coal Mine in Upper Silesia, Poland, *Acta Geophysica Polonica*, Vol. XXVII, No. 1, pp. 39-49.

for this area the activation of the preexisting tectonic component of the local stressfield seemed to be a major factor responsible for the origin of large rockbursts.⁶ Bath,¹ in a study of iron mines in Sweden, concluded that the rockburst mechanism was partly related to mine geometry and partly related to the stress pattern and fracture orientation in the region. Spottiswoode and McGarr¹² in contrast, found that deep mine tremors in very deep South African mines (which can reach depths of 3 km) have a marked similarity to natural crustal earthquakes. Studies of mines in eastern Utah by Smith et al.¹³ agree with the findings of Gibowicz : composite fault plane solutions have P and T stress axes in agreement with the stress pattern attributed to the tectonic regime.

2.3.4 SCALING LAWS DERIVED FROM ROCKBURST SPECTRA

Because of the lack of spectral analyses, little work has been done on rockburst scaling laws.

Stiller et al.⁸ studied the source parameters of seven Polish coal mine events and two East German potash mine events. They included mostly weak events plus one large event ($m_b = 5.4$). Figure 4 is modified from his paper and compares the scaling relation for these events to the relation derived by Chouet et al.¹⁴ for weak earthquakes. The agreement is good and Stiller concludes that the fracture mechanism for the weaker (Type I) rockbursts might be similar to that of the stronger ones (Type II). Also, the slope of the high frequency asymptote, thought to be controlled by the slip velocity and crack propagation, remained constant for events whose moment ranged over seven orders of magnitude. This suggested that the rupture mechanism for events associated with a stope (advancing mine face) may be similar to the larger events (Type II). Spectral data are sparse for many weak events, so these conclusions are tentative.

2.3.5 SOURCE MECHANISM

Hasegawa¹⁵ suggests that the different possible modes of failure can be differentiated in the P and S wave source spectra. Roof collapse would exhibit mainly vertical forces in the earthquake records, tensile failure of cap rock above the mine would show horizontal extensional dipole motion, pillar bursts would show vertical compressional dipole motion, extrusion of the coal seam would exhibit horizontal and vertical force, and faulting would show double couple. Hasegawa further suggests that in the Canadian potash mines (which do not use blasting) the larger events could be caused by two mechanisms: (1) horizontal shear between layers or (2) normal faulting, resulting from mine closure, in the competent layer above the mine face.

-
12. Spottiswoode, S.M. and McGarr, A. (1975) Source parameters of tremors in a deep-level gold mine, *Bull. Seism. Soc. Am.* **65**:93-112.
 13. Smith, R.B., Wikler, P.L., Anderson, J.G., and Scholz, C.H. (1974) Source mechanism of microearthquakes associated with underground mines in eastern Utah, *Bull. Seism. Soc. Am.* **64**:1295-1317.
 14. Chouet, B.K., Aki, K., and Tsujivra, M. (1978) Regional variations of the scaling law of earthquake source spectra, *Bull. Seism. Soc. Am.* **68**:49-79.
 15. Hasegawa, H. (1987) Induced Tremors in Canadian Mines, abstract, paper presented at 59th Annual Meeting of the Eastern Section of the Seismological Society of America, St. Louis University.

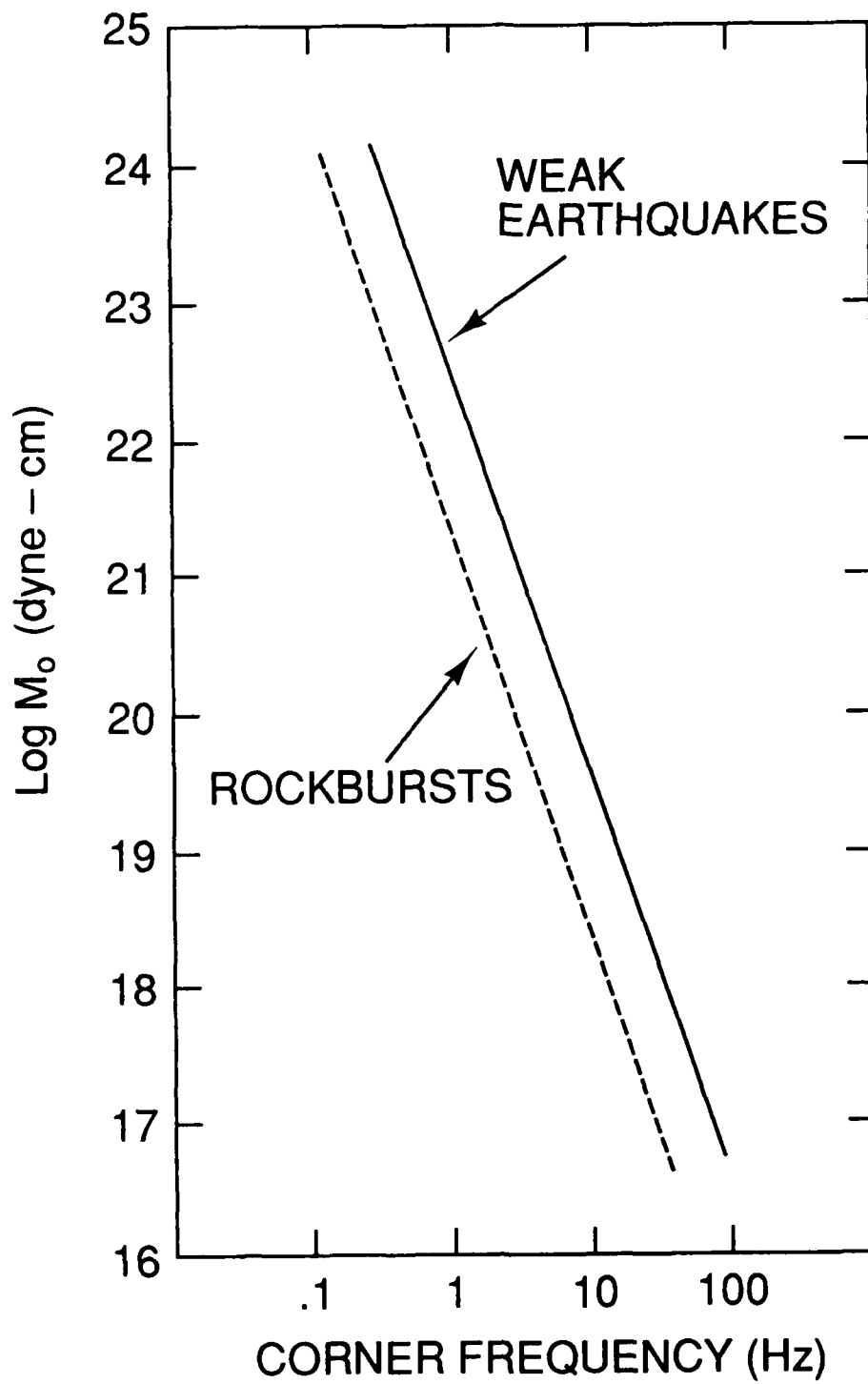


Figure 4. Seismic moment versus corner frequency for weak earthquakes and rockbursts (modified from Stiller et al. (1983)⁸).

Cook (1987 personal communication) suggests that many Type I rockburst events can be considered to be double events: the first element, cracking at the stope walls (Figure 9E, Section 3.6) exhibits high frequency motion; the second element, an implosion or settling of the cavity, is a longer period phenomenon. Indeed, Stiller et al.,⁸ using synthetic seismogram modeling techniques, could successfully discriminate between an explosion induced event (first implosion then shear) and a rockburst (shear then implosion of cavity). Also, in an analysis of over 250 rockbursts in the coal mines of Upper Silesia (Poland) and the Kladno District (Czechoslovakia), recorded from 1977 to 1983, Rudajev et al.⁶ discovered that the records exhibited a dominant shear component with at most a 10 percent implosion (cavity collapse) component.

For Type II events, a major concern is whether the presence of a mine can trigger fault slippage over a fault area that is larger in the length dimension than the length of the mine itself. Also, the effect of mining on faults that transect large mining districts is not clear. Possibly, potential for large induced slippage is greater if there are more mines present. In this scenario, the addition of individual mines might produce a synergistic effect. McGarr (personal communication) notes that a magnitude 4.3 Type II event occurred on a fault in South Africa that cut across two mines. A South African event on November 13, 1986, caused slip on both sides of a mine boundary. In general, the mechanisms seem to be as varied as the geometry of the strata. In the South African mines, the gold bearing reefs have already been offset by normal faults (Figure 5). Thus, the mining itself has created favorable conditions for slip on these surfaces if either of the excavation cavities collapses (McGarr, 1987, personal communication).

2.4 Areas of Rockburst Research

Factors that determine rockburst characteristics are numerous and interrelated. As with natural earthquakes it is generally difficult to isolate the effects of any one influencing factor. Some mine-specific variables that could influence rockburst characteristics in different ways in different areas of the world are:

1. Type of mining operation - geometry, depth of mine, areal extent.
2. Geology - rock mechanical properties, layering, extent of faulting, presence of dykes, likelihood of creep, permeability, water access, fluid pressure in rocks.
3. Tectonics of the area - preexisting stressfield estimates.

The effects of these variables may be manifest in several ways. There have been many local studies on these effects, but they have not been systematically studied on a worldwide scale. This thesis will focus on a comparison of these studies, with particular emphasis on the following phenomena:

1. Changes of local seismicity from natural or pre-mine seismic levels.
2. Magnitude-frequency statistics on the rockburst events:
 - (a) Maximum magnitude, maximum moment.
 - (b) b-value, as related to stress state.
 - (c) Presence of precursors.
 - (d) Energy-time distribution: similarity of energy and magnitude distribution to those of earthquakes swarms or aftershock series.

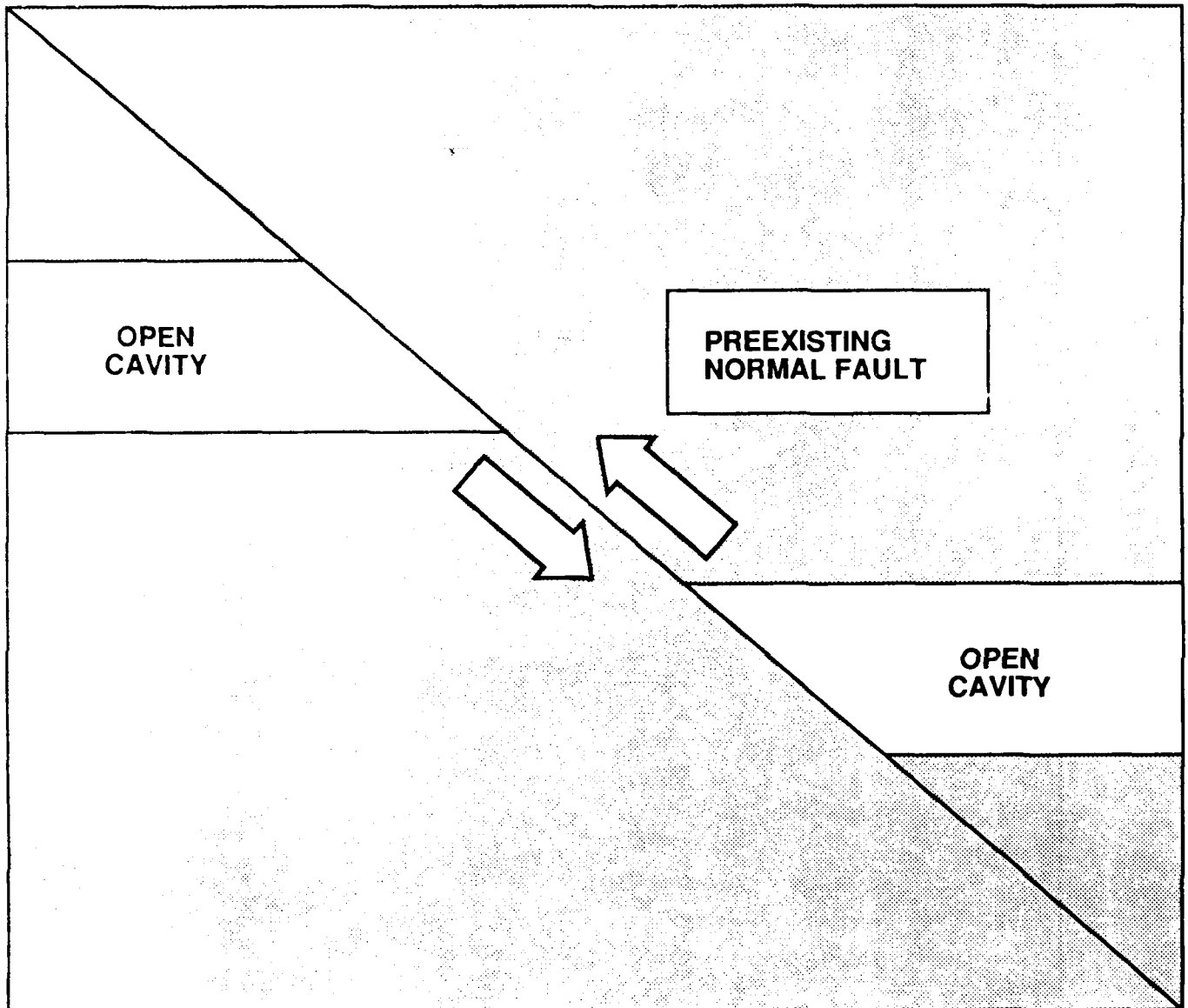


Figure 5. Excavated seam offset by normal faults has a high potential for slipping.

- (e) Stress-drops - similarity of rockburst stress drops to natural crustal earthquakes of similar magnitudes.
- 3. Seismic waveform characteristics:
 - (a) Spectra - corner frequency, moment.
 - (b) Duration - coda magnitude.
 - (c) Fault plane solutions - related to stress state.
 - (d) Presence of non-shear double-couple component.
- 4. Spatial and temporal relationships of rockbursts to the current mining operations.

Section 2 has introduced the relevant methods and parameters for recording and analyzing rockbursts. A description of mining methods (Section 3) is followed by a detailed comparison of rockburst seismicity from a selection of mines in different tectonic terrains (Section 4).

3. TYPES OF MINING OPERATIONS

Several mining methods are employed currently; the choice primarily depends on the type of rock/ore and on economic conditions. Since mining geometry may be an important factor in the initiation of rockbursts, some of the typical techniques are described below. It should be noted that seams, veins, and reefs are approximately two dimensional while lodes are more equidimensional.

3.1 Longwall Coal Mining

In this type of operation a longwall panel is first defined by a series of parallel roadways, and then the panel itself is mined out. Coal is cut out along the coal face; the support system behind the face provides temporary roof support during mining. A gob area (Figure 6) is formed by the collapse of the immediate roof behind the support system.¹⁶ The sequence therefore is: (1) continuous movement of the coal face, (2) advancement of the roof support system, (3) cave-in of unsupported roof. Movement of the loosened roof blocks and crushing of the gob area serve as continuous sources of seismic energy. The pillars developed in the longwall process often can become highly stressed as the longwall passes.

3.2 Room and Pillar

Used often to excavate coal seams or lode deposits, room and pillar workings partially excavate large areas of the seam, leaving a regular pattern of pillars on which the overburden is supported (Figure 7). If the rock pillars cannot support the weight of the overburden, or if the shear stresses exceed the strength of the rock, the pillars can fail violently (pillar burst).

16. Hardy, Jr., H.R. and Mowrey, G.L. (1976) Study of Microseismic Activity Associated with a Longwall Coal Mining Operation Using A Near-Surface Array, *Engineering Geology*, Vol. 10, pp. 263-281.

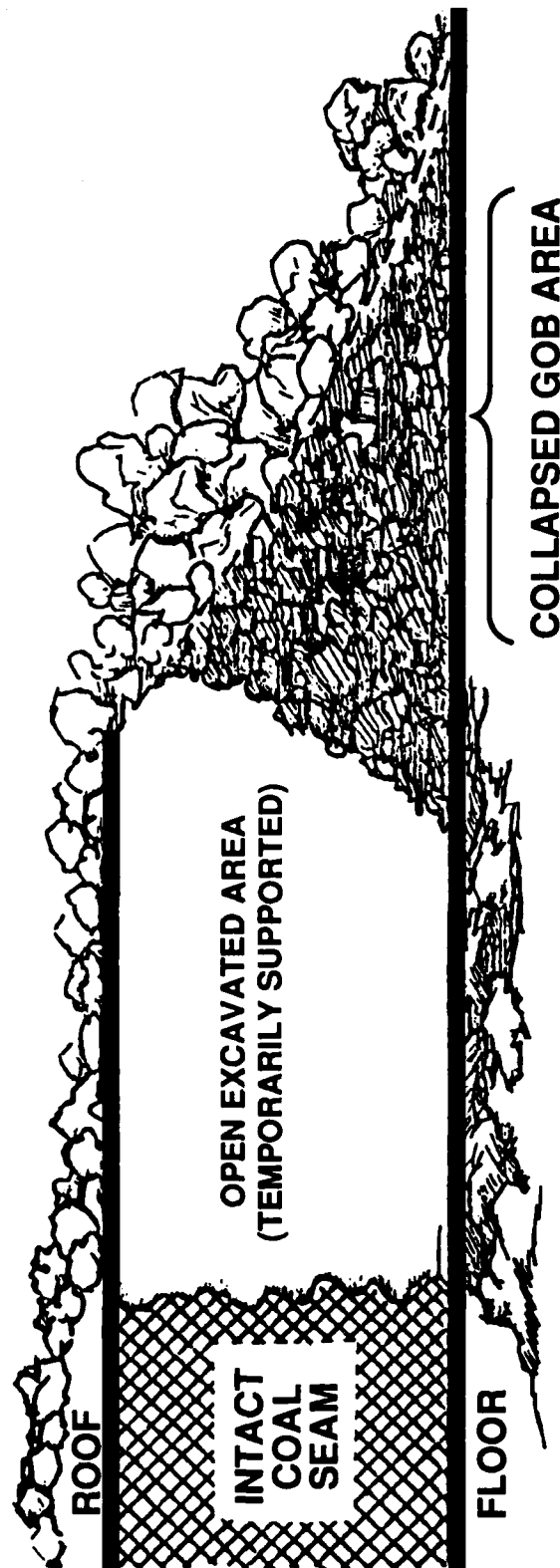


Figure 6. Typical longwall coal mine.

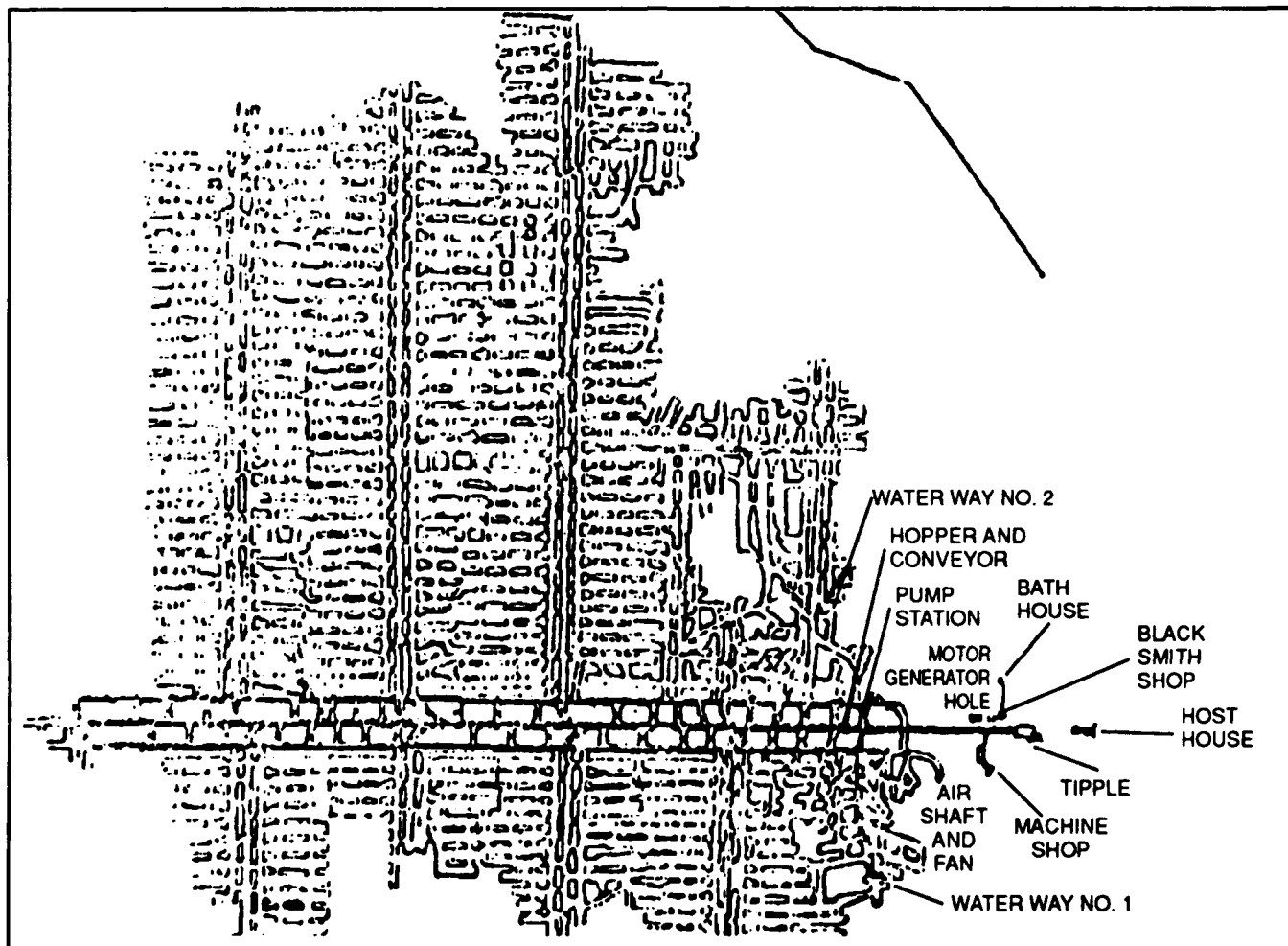


Figure 7. Partial-extraction plan for thin coal, with rooms cut together, from Cummins and Given (1973).¹⁷

3.3 Stopping

Caved stope methods result in fracturing and caving of the strata overlying an excavation. Possibly surface subsidence can result if the caved area is very large. It is best used with thin to moderately thick sedimentary deposits. For large thick deposits of weak ore, block, continuous, or panel caving is used. The caving block generally is prepared by partially isolating its sides and then undercutting the block so that the ore caves in. Alternatively, panels can be cut, but the rock must be weak enough to break into pieces.

3.4 Long Hole Mining

This technique is used for steeply pitching deposits. The material is blasted and then flows by gravity down the pitch to the loading point. This system is illustrated in Figure 8, from Cummins and Given.¹⁷

3.5 Surface Mining

The characteristics of open pit and strip mining systems are correlated to the surrounding conditions of the ore body to be mined.

For pits, which are basically large holes in the ground, the object is to minimize the overall stripping ratio.¹⁷ To accomplish this, the pit slope must be as steep as possible while still remaining stable. Some steep slopes will be stable for periods of months or years and this may be sufficient for extraction of the ore.

Strip mining, often used for coal extraction, is a technique that is usually used when the ore is situated along the outcrop of a flat dipping bed. As in open pit mining, the stability of the slope as the overburden is removed is of major concern.

3.6 Causes of Failure

The type of rock failure is dependent on the type of mining operation. Surface mines can result in slope failures, while in underground mines several types of fractures including rockbursts can occur. If supporting pillars are absent, rock adjacent to the excavation is loaded by the surrounding rock mass.⁷ The techniques often used in deep gold mines create flat voids in strata extending laterally for distances of up to several kilometers with initial thicknesses often on the order of one meter. Geodetic measurements in the tunnels and bore holes in the adjacent rock masses have shown an elastic response over long periods of time to the enlargement of cavities from advancing stope faces. The geometry of this kind of mine leads to a maximum stress concentration at the edges of the excavation as evidenced by rock failures in these areas⁸ or, as in the Witwatersrand system in Africa (Section 4.3.1) by continuous seismicity and new fracture planes that parallel the stope faces.

17. Cummins, A.B. and Given, I.A. (Eds.) (1973) *SME Mining Engineering Handbook*, Vol. II, Soc. of Mining Eng. of the American Institute of Mining, Metallurgical and Petroleum Engineers, Inc., New York, NY.

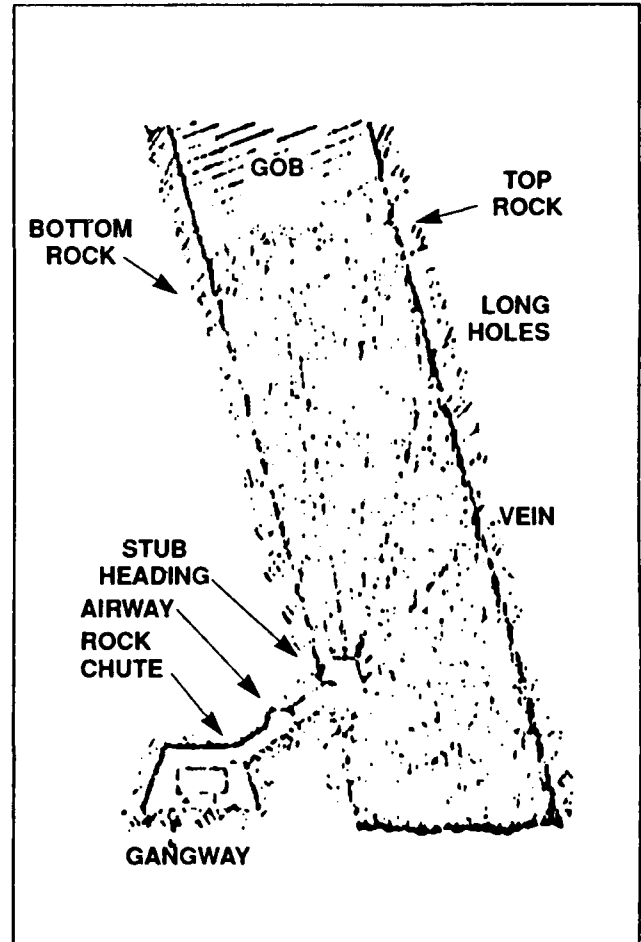
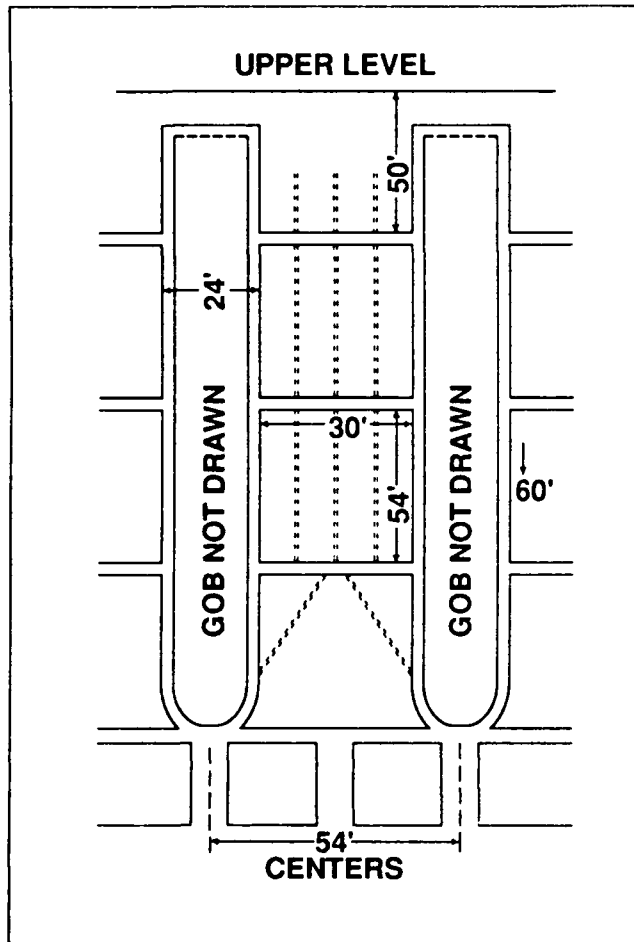


Figure 8. Maximum and minimum development for long-holing: maximum at left with usual chambers and crosscuts but larger pillars; minimum at right with only drill headings in the vein, from Cummins and Given (1973).¹⁷

Figure 9 illustrates some of these failure modes. In Figure 9A, ore is extruded because of high vertical stress from the overburden. Figure 9B illustrates roof collapse. These two modes of failure do not produce rockbursts: The following four modes do produce rockbursts: Figure 9C shows slippage on a preexisting fault; figure 9D shows breaking of intact rock ahead of an advancing mine face; this often results in a high stress drop and rockbursts. In Figure 9E, cracking at the active face as well as cracking at the opposite end of the mine results from stress concentrations at the ends of the excavation. Figure 9F illustrates pillar bursts.

4. INFORMATION ON MINING AREAS

The following sections describe the details of the mines or mining districts reviewed in this thesis. The majority of the studies included were taken from major scientific journals and proceedings of international symposia. The selection unfortunately could not include many studies from less widely distributed literature. Most of the major rockburst problem areas in twelve countries have been tabulated for comparison purposes. These areas are shown in Figure 10. No information was found on South American mines although rockbursts do occur there. The first three sections contain information on the mines that had the most analysis available. Where statistics on mines are described as "not available," the data were not found in publications involving rockbursts but may be available from other sources such as mining logs, bore hole logs, and company records.

4.1 Poland and Czechoslovakia

A great deal of information has been published on rockbursts problems in Poland and Czechoslovakia. A joint project of these two countries has resulted in detailed analyses that cannot all be described in this paper. Unfortunately, much of this information has not been translated into English and has not made its way into international journals. Some general information on the types of mines and specific information on magnitude-frequency relationships and upper limit size estimates is surveyed below.

Most hard coal and copper deposits in Poland are mined at depths of between 600 and 1000 m¹⁸ with the average depth now reaching 665 m.¹⁹

Some success with monitoring of precursory phenomena has been achieved in Polish mines. Gibowicz¹¹ found that five of the largest tremors during his study of over 200 tremors occurred during the lowest b-value intervals (Section 2.3.2).

Also, in an experiment in the Lubin Copper mines (Section 4.1.2), W. Stopinski et al. from the Institute of Geophysics, Polish Academy of Science in Warsaw, tested an electrical resistivity method

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18. Marcak, H. (1984) The Relationship of Microstructure in Stressed Coal Seams to Observed Seismoacoustic Phenomena, in *Geologic Structures and Materials*, held at Pennsylvania State University, Hardy, Jr., H.R. and Leighton, F.W. (Eds.).
 19. Konecny, P., Knejzlik, J., Kozak, J., and Vesely, M. (1983) Rockbursts: Prediction and Control, symposium, organized by the Institution of Mining and Metallurgy in association with the Institution of Mining Engineers, and held in London on 20 October 1983.

MODES OF FAILURE

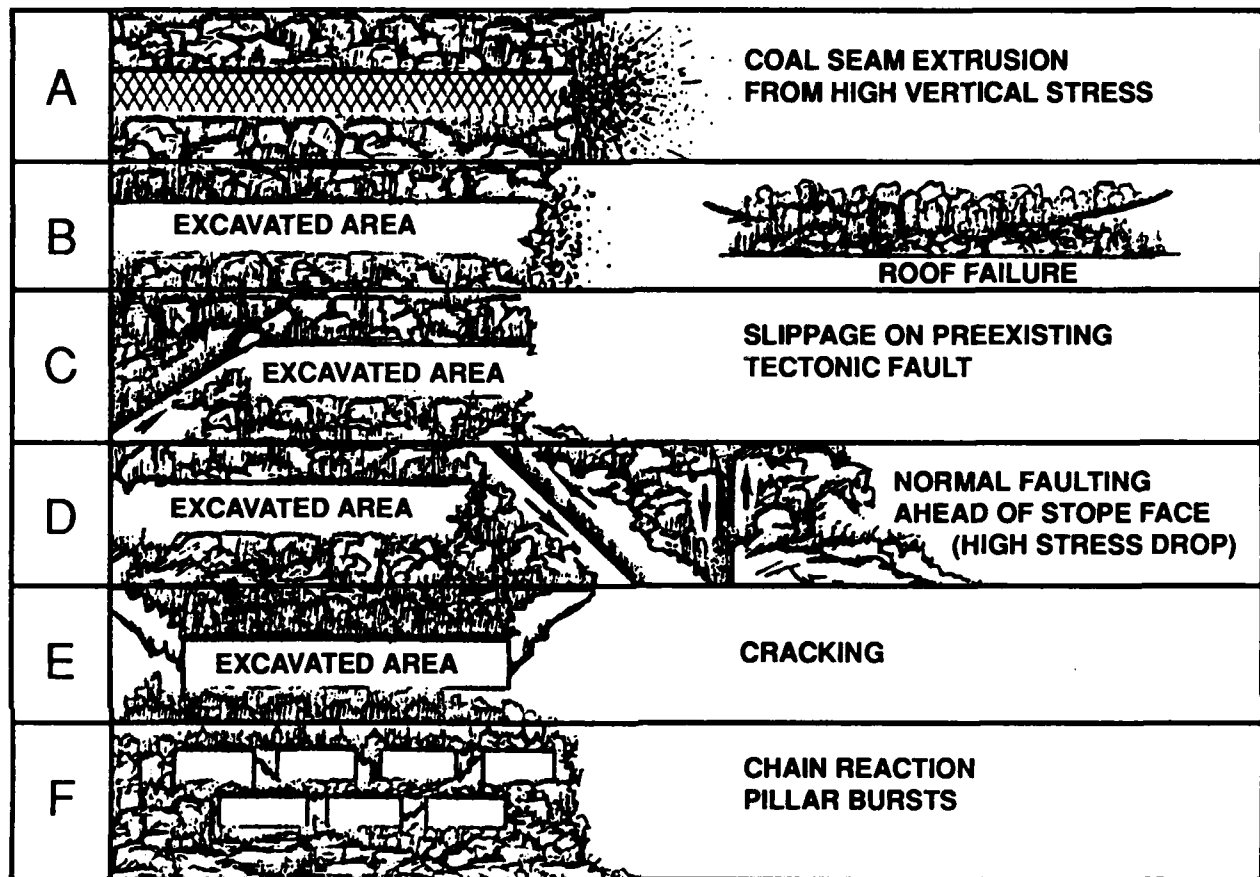


Figure 9. Modes of Failure. (A) coal seam extrusion resulting from high vertical stress, (B) roof failure of excavated area, (C) Type II rockburst event on preexisting tectonic fault, (D) extensional faulting ahead of advancing stope face, (E) cracking at edges of stress concentrator, (F) chain reaction shear failure pillar bursting.

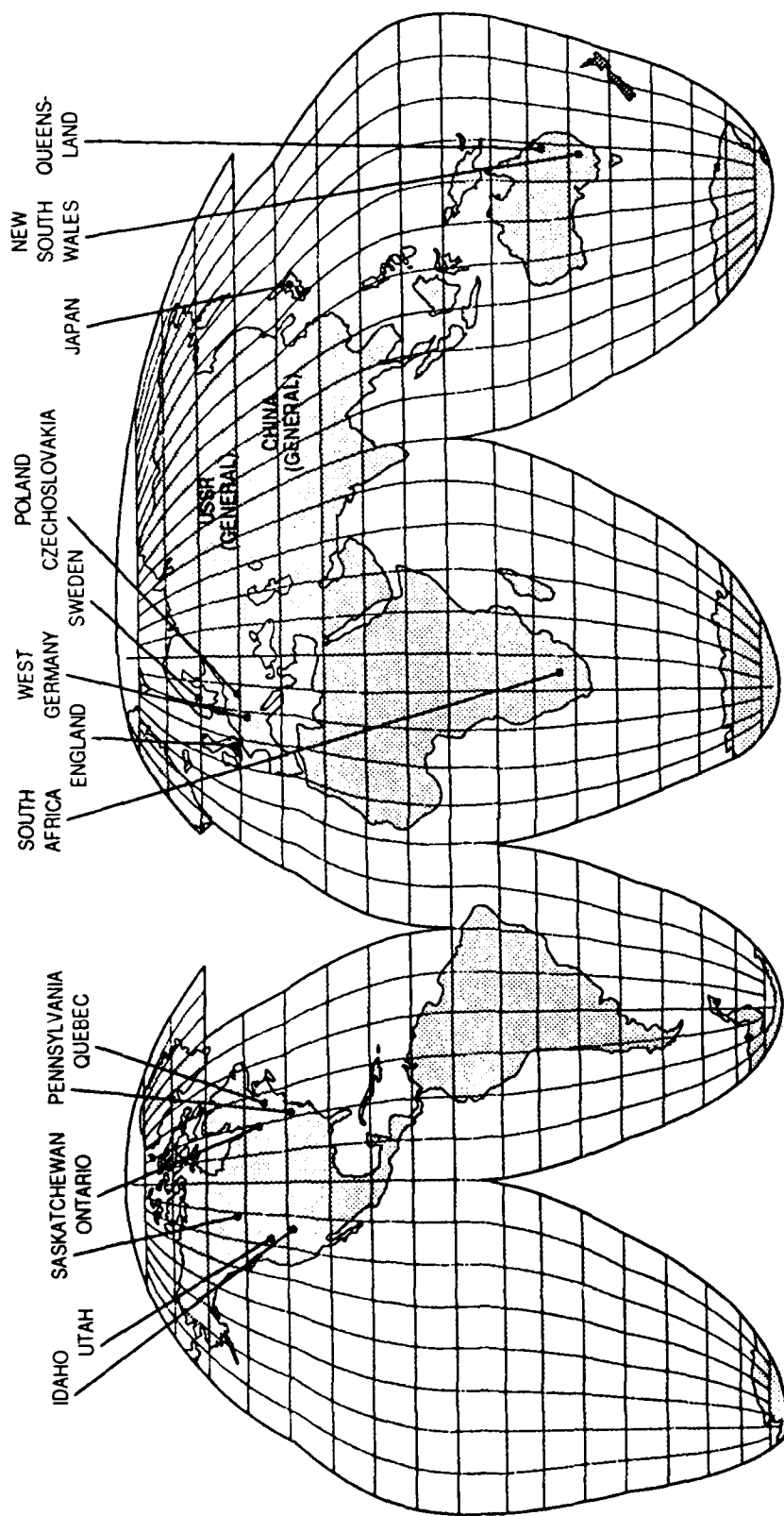


Figure 10. Mining Areas included in this survey. China and the USSR are discussed only generally: there was no information in English on South American rockbursts.

for predicting rockbursts.²⁰ It was found that certain areas of mines experienced characteristic electrical anomalies when there was a danger of a large rockburst. In one case, positive resistivity anomalies led researchers to predict an event; other monitoring concurred (acoustic emissions, etc.). To prevent a rockburst, miners blasted to de-stress the rock, whereupon all the indicators returned to baseline normal (R. Dmowska, personal communication).

4.1.1 UPPER SILESIA COAL BASIN (KARVINA, CZECHOSLOVAKIA)

Ore: Coal.

Geology: The Karvina part of the Upper Silesia Coal Basin is composed of two formations, the Ostrava and the Karvina. The Ostrava has a large number of coal seams with fine-grained marine and paralic sediments in the overlying strata. This formation reaches 1400 m in thickness. The Karvina is younger, 1200 m thick and is composed exclusively of coarse grained continental sediments, mostly conglomerates and sandstones with siltstones and claystones of high strength (80 - 110 MPa). Seams are medium thick to thick. In this formation, 88 seams of average thickness 228 cm have been verified.¹⁹

Mine Depth: 600 - 1000 m

Mining Operation and Area: The rate of production is very high. Normalized per square kilometer, it is three times that of the USSR, West Germany, and Poland.

Monitoring: In 1982 five seismic stations were installed, and nine more were added later. Since the installation, twelve rockbursts and sixty-two "tremors" have been recorded. At least one Type II event has been recorded. Of rockbursts in the Upper Silesia Coal Basin, most have occurred in the Karvina part.

Analysis: Konecny et al.¹⁹ found that the rockbursts were unquestionably related to mining activity, but rockbursts continued at a declining rate over months and even years after some mines were closed. This is in contrast to South Africa (Section 4.3) where the decay time is as short as one day. It was also found that in one zone, seismic activity was absent in the immediate vicinity of the coal face but appeared at greater distances (hundreds of meters) at artificial or natural discontinuities (That is, activity of one mine zone may cause failure at some other mining zone). In some zones induced seismicity declined to zero when mining operations halted.

4.1.2 LUBIN COPPER BASIN (POLAND)

Ore: Copper.

Geology: Not available.

Mine Depth: 600 - 1000 m.

Mining Operation and Area: Not available.

Monitoring: At least since 1972. In one study for 1972 - 1982, 361 tremors were examined.

20. Stopinski, W. and Dmowska, R. (1984) Rock Resistivity in the Lubin (Poland) Copper Mine and Its Relation to Variation of Strain Field and Occurrence of Rockburst, in Assessing Underground Hazard, Gay, N.C. and Wainwright, E.H. (Eds.), Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg, 1984.

Analysis: In the Lubin Copper Basin, Gibowicz²¹ studied source parameters of events in a sequence that occurred from 1975 to 1983. He concluded that for small magnitudes ($M_L \leq 3.0$), the local magnitude was a direct measurement of moment. For source radii less than 0.5 km, the relationship derived was

$$M_L = \log M_0 - 10.16$$

where M_L is the magnitude and M_0 is the seismic moment.

Based on the relationship of source radius, r , to M_0 , it was found that the source radius was independent of seismic moment (for M_0 between 2×10^{11} and 2×10^{13} Nm). For this study, the source radii ranged from 70 to 502 m, with the average value about 190 m.

For the March 24, 1977 tremor, $M_L = 4.5$, a normalized seismic moment M_m of 5.14 and seismic energy E_s of 2.5×10^{10} J were computed.

Gibowicz concluded that although values of local magnitude for M_L less than 3 are direct measurements of the seismic moment, for a given seismic moment, corresponding source radii can vary by a factor of six to seven.

A successful prediction experiment was conducted by W. Stopinski using electrical resistivity methods (see general comments, Section 4.1).

4.2 Canada

Rockbursts have occurred in the hard rock mines of Kirkland Lake and Timmins in Ontario, and Normental Mines in Quebec. Incidents of rockbursts have declined in recent years, but large events still occur. Much of Canada's hard-rock underground mining is conducted in the province of Ontario, and most rockbursts occur there. But there have also been rockbursts at Brunswick Mining and Smelting (lead and zinc) in New Brunswick, at the potash mines in Saskatchewan and some isolated events in the Val D'Or gold mining district in northwest Quebec.²²

Responding to new economic pressures, Canadian mines are now stepping up activity. Many of the mining operations are in the last stages of recovery, and economic factors have pushed the operations to greater depths and larger areas of extraction. Because of the increased mine activity, rockbursts have again become a topic of interest.

H.S. Hasegawa (Ref. 15 and personal communication) summarized what is known about induced mining seismicity in Canada. The sparsity of seismic stations hampers accurate location of rockbursts, especially since rockbursts occur in mines that may be far from high seismicity zones. The author knows of only three fault plane solutions for Canadian rockbursts and even these are composites (constructed from several events, implicitly assuming that each had the same mechanism).

21. Gibowicz, S.J. (1985) Seismic Moment and Seismic Energy of Mining Tremors in the Lubin Copper Basin in Poland, *Geophysica Polonica*, Vol. XXXIII, No. 3, pp. 243-257.

22. Udd, J.E., Hedley, D.G.F. (1987) Rockburst Research in Canada - 1987 in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpaisal, S. (Eds.), Vol. 2, pp. 1283-1288.

The main reason there is little spectral information from Canadian rockbursts, despite the numerous mines that have geophone networks, is that these networks typically do not store the wave form (I. Wong, personal communication). The systems are designed to count events and record arrival times for the purpose of location but frequently magnitude and waveforms are not retained.

One fact that is known is that the maximum horizontal stress is much greater than the vertical ($\sigma_h > \sigma_v$) by a factor of up to 3. This should have an influence on the mechanism (in contrast to South Africa, where $\sigma_h < \sigma_v$).

In Ontario, stresses vary greatly with depth, possibly remnants of residual stress from an ancient orogeny (Hasegawa, 1987, personal communication).

Occasionally in the deep Maritime coal mines, the high pressures and temperature favor violent extrusions of coal into the openings. Metalliferous mines in the south central Canadian craton experience the largest rockbursts on faults above the mine.

4.2.1 ONTARIO

Of 217 rockbursts recorded in Ontario mines during 1984 and 1985, 5 percent were classified as strain energy bursts, 81 percent as pillar bursts (Section 3.2), and 14 percent as fault slip bursts (Type II). The magnitudes ranged from 1.5 to 4.0 on the Richter scale.²²

4.2.1.1 Kirkland Lake Gold Mining District

Ore: Gold.

Geology: The lakeshore fault of the Kirkland Lake gold mining district is an undulating strike-slip fault.²³ The area can be characterized as having hard rock. Extensive geological literature is available.

Mine Depth: This district contains the deepest mines in North America. The Lakeshore and Wright-Hargreaves mines reach depths of 2,461 m and 2,491 m, respectively.

Mining Operation and Area: Not available

Monitoring: The author was unable to find any information on networks. Between 1939 and 1943, thirteen of the rockbursts from this area were large enough to be recorded in Ottawa over 900 km away. A severe rockburst on May 5, 1964, resulted in the closure of the Wright-Hargreaves mine.

Analysis: After a change in mining practices (avoidance of irregular mine geometries and smaller scale blasting) smaller events occurred through the late 1940's.²⁴

4.2.1.2 Quirke Mine, Elliot Lake

Ore: Uranium

Geology: A dipping, strong brittle quartz layer with high horizontal stress ($\sigma_h : \sigma_v = 2:1$)

Mine Depth: 500 m.

23. Wallace, R.E. and Morris, H.T. (1986) Characteristics of Faults and Shear Zones in Deep Mines, *PAGEOPH.* Vol. 124, Nos. 1/2.

24. Hodgson, E.A. (1958) *Dominion Observatory Rockburst Research 1938-1945*, Publ. Dominion Obs., Vol. 20, pp. 1-248.

Mining Operation and Area: 1100 m × 600 m, room and pillar.

Monitoring: A network was installed from September 1984 to April 1985. During this period 150 pillar burst type events were recorded in a area of 1 km².

Analysis: Rockburst activity in this area has fluctuated considerably in recent years. In 1982, there was a large series of rockbursts²² followed by a quiet period of two years. In 1984 - 1985 there were 150 events as described above. No information on mining rates is available to allow correlation.

4.2.1.3 INCO Mines, Sudbury

Ore: Nickel.

Geology: The Creighton mine ore body consists of a low grade norite.¹⁷ See Ontario geology, Section 4.2.1.

Mining Operation and Area: Three nickel mines of the INCO Metals Company, Ltd.

Monitoring: The mines were instrumented in the mid 1940's. In mid 1984 two major series of rockbursts occurred in the Sudbury area.

Analysis: No precursory information has been observed except that prior to a burst the frequency content of the activity seemed to increase.²⁵ For the 1984 events, the mechanisms were related to Type II fault slippage.

4.2.2 QUEBEC

As in the rest of Canada, rockbursts have declined in recent years, but major events still occur. On August 21, 1975, for example, a rockburst with a magnitude of 3.9²⁶ in Malartic, Quebec caused minor damage.

Wallace and Morris²² suggest that in the O'Brien gold mine, irregularities on the mineralized fracture (vein) might generate the asperities that on active faults would serve as stress concentrations, locations of earthquakes or barriers separating slip segments.

4.2.3 SPRINGHILL COAL MINE

Ore: Coal.

Geology: Not available.

Mine Depth: Less than 1000 m.

Mining Operation and Area: Room and pillar above 2000 feet, longwall below.

Monitoring: A deep network was installed that monitored microearthquakes.

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25. Pakalnis, V. (1984) Strengths and Limitations of Microseismic Monitoring for Rockburst Control in Ontario Mines, in *Geologic Structures and Materials*, held at Pennsylvania State University, Hardy, Jr., H.R. and Leighton, F.W. (Eds.), (1987) Strengths and Limitations of Microseismic Monitoring for Rockburst Control in Ontario Mines, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpatsal, S. (Eds.), Vol. 2, pp. 552-558.
26. Milne, W.G. and Berry, M.J. (1976) Induced Seismicity in Canada, *Eng. Geol.*, Vol. 10, pp. 219-226.

Analysis: Activity generally increased before a large event occurred; however, the level of the activity previous to one very large event that triggered many rockbursts did not rise substantially higher. So using "foreshocks" to predict large failures was only moderately useful in this case.¹⁵

4.2.4 SASKATCHEWAN, CORY AND ESTERHAZY POTASH MINES

Ore: Potash.

Geology: The most competent layer is carbonate.

Mine Depth: 7,100 m.

Mining Operation and Area: Continuous (no blasting).

Monitoring: Basically, the events were recorded by the Canadian regional network, which has been in operation for decades.²⁷ Very little information is available because these mines were not instrumented with local arrays until 1980. The recorded seismicity from these local installations is not necessarily mining induced.

Analysis: The largest events occur near the edge of the excavations (Type I events, Figure 9E). Since the technique used is continuous, the seismicity is ascribed to closure at the ends.²⁸

4.3 South Africa

South African gold mines provide more information, data, and analyses than any other mining district in the world. A large portion of the work has been performed by McGarr²⁹ who has found tremors in these deep gold mines to be similar to natural crustal earthquakes in some respects and different in others. The tectonics of the region are generally extensional with the ratio $\sigma_v : \sigma_h$ approximately 2:1 (McGarr, personal communication).

In general, increase in the rate of energy release per unit area with the extent of excavation has gained universal acceptance in planning layouts of stoping in South African gold mines. Cook states that the rate of energy release determines the magnitude-frequency relationship (Section 2.3.5). The greater the rate of energy released, the greater the proportion of large events (Figure 11).

Except for some changes in rate of tilt and displacement before some major events, reliable precursory phenomena have not been discovered. The incidence of seismic events is found to follow a linear log-frequency magnitude relationship.

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27. Gendzwill, D.J. (1984) Induced Seismicity in Saskatchewan Potash Mines, in *Assessing Underground Hazard*, Gay, N.C. and Wainwright, E.H. (Eds.), Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg, 1984.
 28. Herget, G., Mackintosh, A.D. (1987) Mining Induced Stresses in Saskatchewan Potash Mines, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpaisal, S. (Eds.), Vol. 2, pp. 953-957.
 29. McGarr, A. (1971) Violent Deformation of Rock Near Deep-Level, Tabular Excavation: Seismic Event., *Bull. Seism. Soc. Am.* **61**:1453-1466.

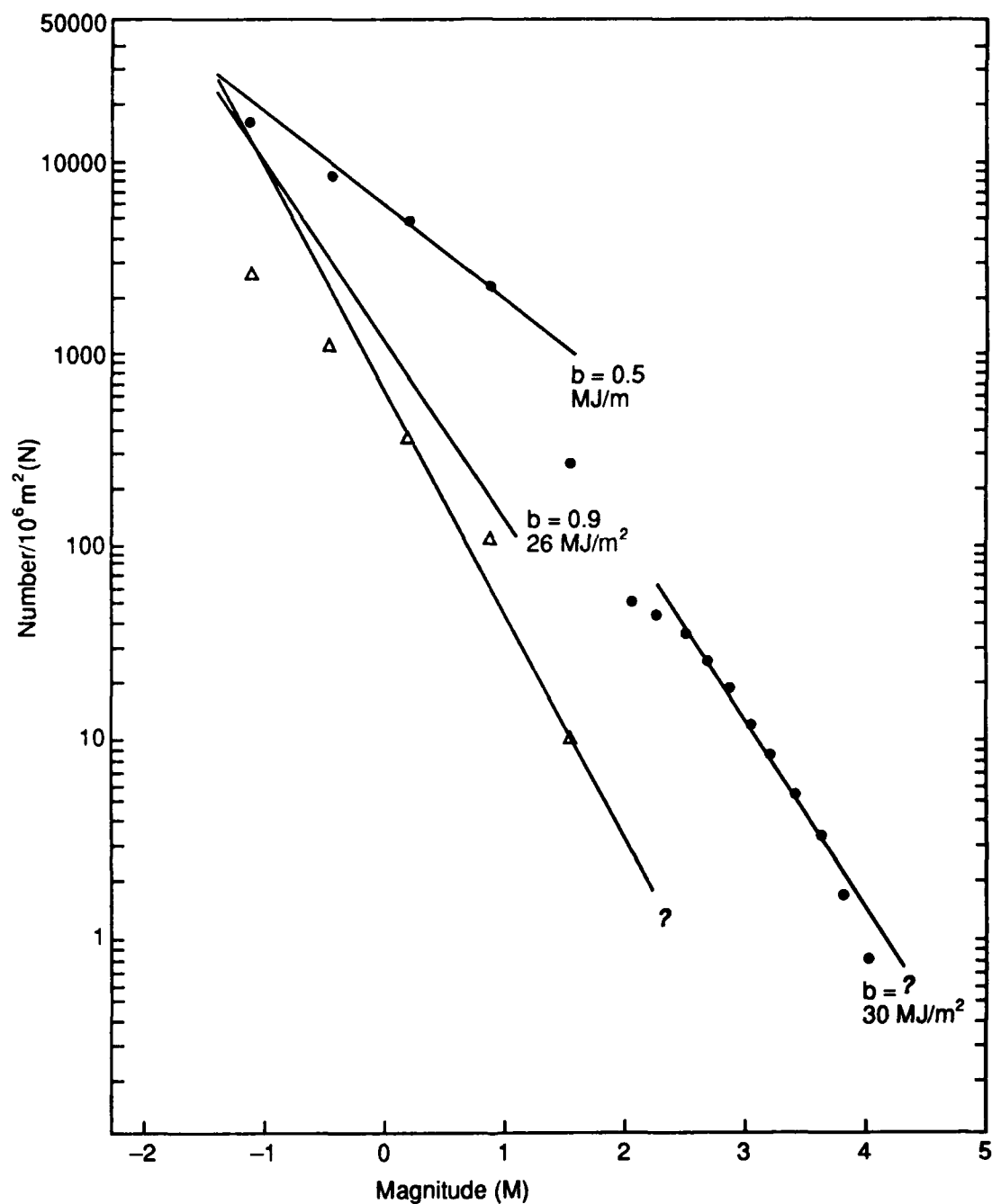


Figure 11. Plots of the logarithm of the cumulative number of seismic events greater than a given magnitude as a function of magnitude. The three lines in the top left are derived from underground seismic observations and that in the bottom right from a surface seismic station. (After Fernandez.³⁰) Note that the slope of these lines is a function of the spatial rate of energy release.⁷

30. Fernandez, L.M. (1973) Seismic Energy Released by the Deep Mining Operations in the Transvaal and Orange Free State During 1971, S. Afr. Deep Mines Geol. Survey.

Statistically, in South Africa more rockbursts have occurred in the vicinity of dykes and major faults than in other areas. Also fracture planes usually terminate on bedding planes. Most of the events give rise to new fracture planes parallel to the boundaries of the mine excavation. Therefore geologic structure can play a major role in the location of rockbursts.

Decay times after cessation of mining are swift in South African mines. Often a significant decrease in the number of rockbursts is observed only one day after mining stops.

In general, McGarr has found the b-value in the expression $\log N = a - bM_L$, where N is the events per time of magnitude greater than or equal to M_L , to be stable over a particular region, whereas the a-value appears to be a property of the geologic formation and the strain rate.³¹

4.3.1 WITWATERSRAND SYSTEM

Ore: Gold.

Geology: The effects of geologic structure in the Witwatersrand have been summarized by Cook⁷. The sediments vary significantly in their mechanical properties and are cut by faults and intruded by dykes and sills. The strength of these Witwatersrand quartzites is typically given by $\sigma_1 = 200 \text{ MPa} + \sigma_3$. Strain measurements from 1.5 to 2.5 km depth in relatively undisturbed sediments in the Witwatersrand system were tabulated by Pallistor³² and show that the magnitudes and directions of the principal horizontal strains varied greatly with depth (Figure 12) as is found in Canadian shield areas.

Mine Depth: 3 km.

Mining Operation and Area: Gold reefs mined down to 3 km depth by stoping.

Monitoring: Various arrays. The maximum size of events ranged from 4.0 to 5.0. The magnitude-frequency relationship was linear.

Analysis: Studies have been made of fractures in several gold mines of the Witwatersrand system. These mines are gold reefs mined down to 3 km depth by stoping (see Section 3.3).

The foci of Type I events with magnitudes ranging from very small to greater than 3.0 occur within tens of meters of the advancing stope face. Cook⁷ found that the rate and magnitude of these seismic events can be predicted statistically by the spatial rate of energy release associated with the extension of the excavation.

In two mines studied by Cook and Joughen, Cook⁷ found that epicenters of Type I seismic events were within 20 m of the advancing stope faces. However, the elevations of the foci were different. For one mine at which a quartzitic stratum above the reef was less argillaceous than the material below, the foci tended to fall above the reef; in another mine in which the strata adjacent to the reef were both highly quartzitic but with a weak layer of shale at 80 m above the reef, the elevations of the foci tended to fall under this layer. The only precursory indicator of rockbursts in this area is the arrest of tilt before an event.

Also, the m_b to M_L ratio was found to be similar to that for nuclear explosions.

31. McGarr, A. (1976) Dependence of Magnitude Statistics on Strain Rate, *Bull. Seismol. Soc. Am.* **66**:33-44.

32. Pallistor, G.F. (1968) The Measurement of Virgin Rock Stress, M.Sc., Fac. Engineering Univ. Witwatersrand.

4.3.2 KLERKSDORP DISTRICT

Ore: Gold.

Geology: Extensional, normal faulted, hard rock, argillaceous to siliceous quartzites, with subordinate conglomerate and shale horizons.³³

Mine Depth: Average depth 2 - 3 km.

Mining Operation and Area: Four large mines, average area 200 km² (Gay et al.³³).

Monitoring: A digital network was installed in 1986. Most of the events recorded by the network are smaller than 3.0 magnitude³⁴. A large type II event (magnitude 5.2) occurred (see analysis section below). In ten years over 6,000 events were recorded of Richter magnitude between 0.2 and 5.4.

Analysis: McGarr et al.³⁴ observed that in the Klerksdorp district, rockbursts with magnitudes as high as 5.2 seem to be associated with slip on preexisting normal faults that offset the strata (Figure 5, Section 2.3.5). (These would be Type II events.) Here it was found that the source parameters and ground motion parameters were similar to natural crustal earthquakes. The large 5.2 magnitude event was analyzed and found to have a source radius of 84 m and stress drop of 23 bars.

4.3.3 CARLETONVILLE

Ore: Gold.

Geology: Unfaulted, intact, hard rock.

Mine Depth: 2 to 4 km.

Mining Operation and Area: Not available.

Monitoring: Digital network installed in 1986. From May to October, 1986, 22 events of magnitude greater than 3.5 were detected. The upper limit³⁴ appears to be 4.0. (This 4.0 magnitude event had a peak acceleration of 0.045 g with a stress drop of 376 b.)

Analysis: In Carletonville, which does not have substantial faulting, failures of relatively intact rock result in high stress drops and ground motion parameters.³⁴ This is in contrast to the faulted Klerksdorp formation discussed in Section 4.3.2.

4.3.4 EAST RAND PROPRIETARY MINES

Ore: Gold.

Geology: This area has phenomenally hard rock with uniaxial strengths recorded from 4 to 6 kilobars.

Mine Depth: 2 - 3 km.

Mining Operation and Area: 300 m longwall and strike pillars.

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33. Gay, N.C., Spencer, D., Van Wyk, J.J., and Van Der Heever, P.K. (1984) The Control of Geological and Mining Parameters in the Klerksdorp Gold Mining District, in *Assessing Underground Hazard*, Gay, N.C. and Wainwright, E.H. (Eds.), Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg, 1984.
34. McGarr, A., Bicknell, J., Sembera, E., and Green, R.W.E. (1987) Analysis of Exceptionally Large Tremors in Two Gold Mining Districts of South Africa, presented at Fred Leighton Memorial Workshop on Mining Induced Seismicity, 29-30 August 1987, Montreal, Quebec.

Monitoring: Various digital arrays. Dates of operation were not available at this time. An event of M_L greater than 2.0 occurred about every 12 days.³⁵ The maximum size of events was 2.8 for Type I, 3.8 for Type II.

Analysis: Spottiswoode and McGarr¹² computed the spectra of 24 tremors from P and S waves recorded from the surface. The tremors were located near the mining faces at depths near 3.2 km and the magnitudes recorded ranged between 0 and 3. They found the spectra to be flat at low frequencies with a fall off according to inverse frequency cubed at high frequency. Using a Brune⁵ type analysis, in which source dimension is assumed to be inversely proportional to corner frequency, source dimensions of 50 to 500 m and stress drops of 5 to 50 bars were inferred. Estimated moments varied from 10^{18} to 10^{21} dyne-cm.

One of the events, a magnitude 2.9 (Pretoria) caused severe damage in regions distributed over a 0.5 km radius in the mine. However, the damaged areas were not continuous. There were virtually unaffected areas between violently damaged zones, suggesting that the event consisted of a series of discrete, separated ruptures. Stress drops for this mine were found to be greater than those estimated by Smith et al.¹³ for seismic events in eastern Utah coal mines, even though source radii are comparable. This is possibly caused by the high strength of the rock in the African mines.

4.3.5 BLYVOORVUITZICHT

Ore: Gold.

Geology: Predominately quartzites with a uniaxial strength of 250 MPa.³⁶ Many diorite dykes cut through the reef.

Mine Depth: 2 - 3 km.

Mining Operation and Area: Four mines engaged in longwall mining procedures; longwalls are long and straight.

Monitoring: Various arrays since 1978.

Analysis: McGarr³⁵ studied b-values for this area. He found that they varied from 0.65 to 0.97.

Spottiswoode³⁶ studied source mechanisms for eleven rockbursts of magnitudes 1 to 2 using body wave spectra. He found zero volume change in the source region (that is, pure shear movement). Source mechanisms showed slip on zones striking parallel to the advancing face or to either of the dykes cutting across the face. Source radii of 25 to 65 m with stress drop of 0.5 to 5 MPa were found (consistent with other mine tremors).

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35. McGarr, A. (1982) Some Applications of Seismic Source Mechanism Studies to Assessing Underground Hazard, Gay, N.C. and Wainwright, E.H. (Eds.), Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg, 1984.
 36. Spottiswoode, S.M. (1984) Source Mechanisms of Mine Tremors at Blyvoorvultzicht Gold Mine, Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, Gay, N.C. and Wainwright, E.H. (Eds.), SAIMM, Johannesburg, 1984.

4.4 United States of America

The United States, like Canada, encompasses tectonic terrain that varies from intraplate mechanisms (New Madrid Seismic Zone) to major tectonic plate boundaries (San Andreas Fault System). In this country, also, there have been no cross correlation studies from one mining area to another. For some areas, extensive literature on the geological formations in the mining area is published (many are US Geological Survey Open File reports). However, for some of the mines for which this is available, the author was unable to obtain any information on rockburst problems.

4.4.1 BOOK CLIFFS AND EASTERN WASATCH PLATEAU EAST-CENTRAL UTAH

Ore: Coal.

Geology: Numerous and complex joints and faults.

Mine Depth: Not available.

Mining Operation and Area: Not available.

Monitoring: A regional network in operation for several years.

Analysis: Coal mining in this area has been associated with some of the highest microseismicity in the country. Although the area is naturally seismic, a large portion of the seismic activity is definitely connected with mining.³⁷ Both Type I events, occurring in the immediate vicinity of the mine, and Type II events have been observed. The Type II events have occurred up to 2 km away from the mine and have been as deep as 3 km beneath the mine. Fault plane solutions are consistent with the horizontal tectonic stress field.

4.4.2 SUNNYSIDE COAL MINING DISTRICT, EASTERN UTAH

Ore: Coal

Geology: A 4 m thick coal seam, underlain by thick, strong, thick-bedded sandstone, 60 to 100 cm thick. This is overlain by a weak 45 m thick shale and sandstone bed.¹³

Mine Depth: Not available

Mining Operation and Area: Room and pillar.

Monitoring: A microearthquake study recorded events from magnitudes less than -1 to 2.8. The zone of greatest activity was located at 1 km depth. Depths of events are in the 1 to 3 km range for events in the 1.2 to 2.8 magnitude range.

Analysis: Stress drops ranged from 0.2 bar for a moment of 2.4×10^{17} dyne-m to 9.6 bar for a moment of 63×10^{17} dyne-cm. Corner frequencies range from 10 to 14 Hz.

A composite fault plane solution showed thrust faulting (compression). The strike of the nodal planes and the direction of the P (maximum compressive stress axis) were in agreement with the presumed tectonic stress pattern, according to Smith et al.¹³ They suggest that the main earthquake energy can be derived from the regional tectonic stress.

37. Wong, I.G. (1985) Technical Note, Mining-induced Earthquakes in the Book Cliffs and Eastern Wasatch Plateau, Utah, U.S.A. *Int. J. Rock Mech. Min. Sci. and Geomech. Abstr.* Vol. 22, No. 4, pp. 263-270, Printed in Great Britain.

Rates of activity averaged hundreds per day. The smallest events appear to have originated as shear failures near the mine walls.

4.4.3 TINTIC MINING DISTRICT, CENTRAL UTAH

Ore: Gold.

Geology: Wallace and Morris²², noted large vertical irregularities.

Mine Depth: Not available.

Mining Operation and Area: Not available.

Monitoring: Not available.

Analysis: Not available.

4.4.4 COEUR-D'ALENE MINING DISTRICT, NORTHERN IDAHO

Ore: Metals

Geology: Wallace and Morris²³ summarized the geology of the Coeur-d'Alene mining district as an intensely faulted and sheared structural knot. A major structural element in the area is the Osborne fault. The rocks involved in the faulting are of Precambrian age and range from fine-grained argillites and siltites to coarse-ground quartzites, with low grade metamorphism of strata.

Mine Depth: Not available.

Mining Operation and Area: Not available.

Monitoring: Not Available.

Analysis: Not available.

4.4.5 STAR MINE (AND ADJACENT), NORTHERN IDAHO

Ore: Lead, zinc, copper.

Geology: The ore occurs in steeply dipping fracture-filled veins. The local rocks are hard and brittle and have high horizontal stress. (See geology of Coeur-d'Alene above).

Mine Depth: It is one of the deepest lead-zinc mines in North America with 200 foot intervals reaching down to almost 8,000 feet.

Mining Operation and Area: The Star Mine produces approximately 1,000 tons of lead, zinc, and silver ore per day, using a horizontal, timbered cut and fill method.³⁸ It is an old mine, in operation since the 1880's, which has complicated opening geometry.

Monitoring: Microseismic monitoring has been performed at the Star Mine, the Lucky Friday Mine, and ASARCO's Galena Mine. In 1975, a 24 geophone network was installed to monitor activity of the Star Mine (Figure 13).

Analysis: The bursts seem to be associated with a several hundred foot wide hard quartzite band that traverses the center of the main vein ore body at a sharp angle. A summary of the log for the

38. Langstaff, J.T. (1980) Interpretation of Acoustic Emission Data in the Star Mine, in Proceedings 2nd Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Hardy, Jr., H.R. and Leighton, F.W. (Eds.).

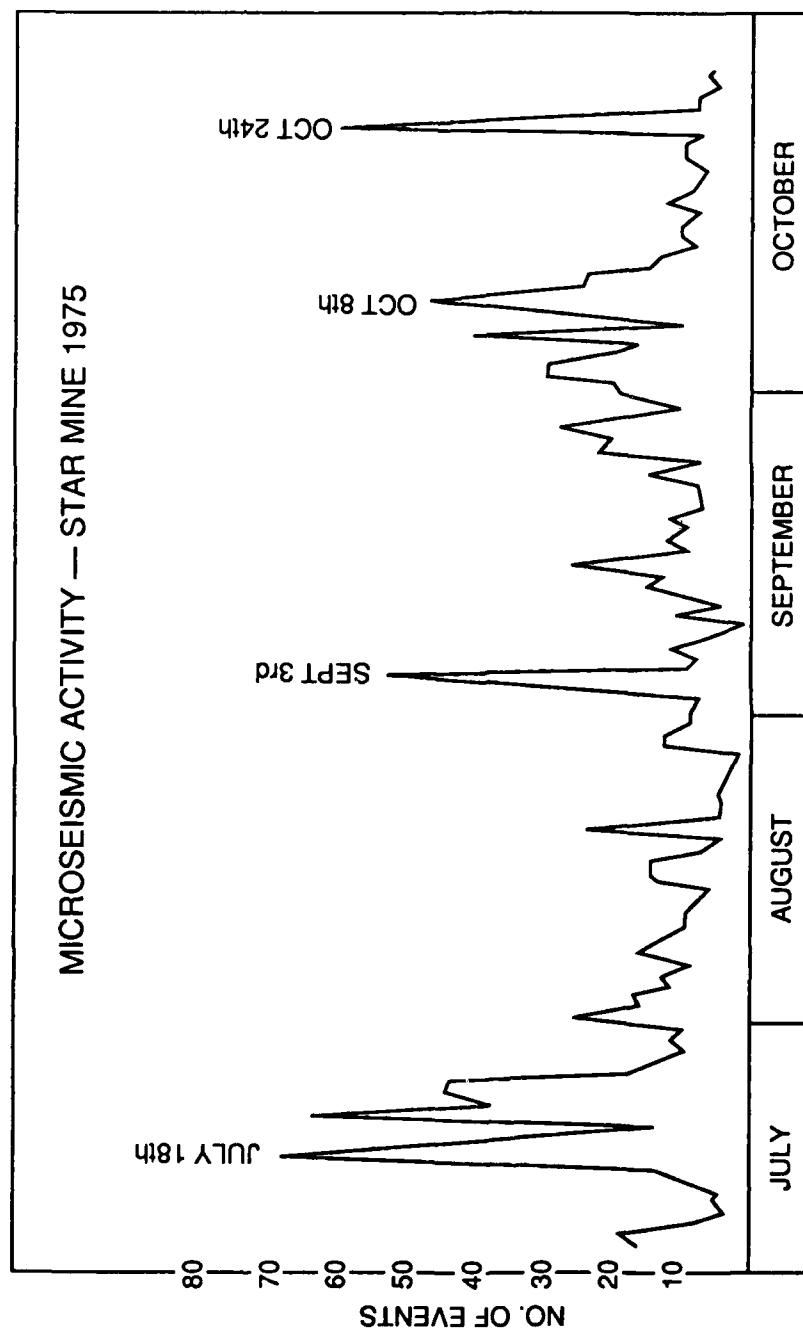


Figure 13. Microseismic activity at the Star Mine, July through October, 1975 (from Langstaff (1980)³⁸).

period illustrated in Figure 13 shows a lack of correlation of rockbursts with acoustic emission (A.E.). An excerpt from the Langstaff³⁸ study is reproduced below:

"- A fairly small burst (8 mm displacement) on August 4 was preceded by a dramatic A.E. buildup."

"- A small burst (3 mm) on August 14th that occurred with blasting was not accompanied by an increase in A.E."

"-A large burst (39 mm) on August 15th, that occurred with blasting was not accompanied by any increase in A.E."

"- A very large burst (120 mm) occurring out in the wall on the 16th was not accompanied by any increase in A.E."

"- A small burst (2 mm) occurring on the 17th was not accompanied by any increase in A.E."

"- An increase in A.E. on the 25th was not followed by a burst."

"- An increase in A.E. on the 29th was not followed by a burst."

4.4.6 CENTRAL PENNSYLVANIA

Ore: Coal.

Geology: Not available.

Mine Depth: 600 feet.

Mining Operation and Area: Longwall with blasting.

Monitoring: A geophone array was installed to monitor microseismicity. Hardy and Mowry¹⁶ found the majority of computed depths for hundreds of events recorded from the array to lie within 100 feet of the coal seam.

Analysis: The rate of micro-activity was found to fall off dramatically during shift changes. Also, activity increased for about 5 minutes after major blasts.

4.5 Grangesberg Mines, Central Sweden

Ore: Iron.

Geology: The mine consists of a dipping slab with an ore body surrounded by lepte and granite.

Mine Depth: 550 m.

Mining Operation and Area: Not available.

Monitoring: A large rockburst, $M_L = 3.2$, occurred in August 1974, and was studied by Bath.¹ It was followed by a long sequence of events of character between that of swarms and aftershocks. A network was installed, which recorded over 1000 events in under 4 years.

Analysis: A focal mechanism was determined for the large event and showed a shear failure, not compression, which led Bath to speculate that collapsing of cavities was the exception rather than the rule (at least in this area). The results of magnitude-frequency study show:

$$\log N = 3.04 \pm 0.1 - (1.08 \pm 0.05) M_L$$

for $1.1 \leq M_L < 3.2$ for a complete data set. The value (1.08 ± 0.05) is larger than the value determined for (natural) earthquakes occurring in Sweden ($b = 0.85 \pm 0.02$). This was translated into an energy-magnitude relationship. The main shock contributed only 16 percent of the energy released over the four years, thus the series was more similar to an earthquake swarm in this respect. However, the

energy-time relationship is more characteristic of an aftershock series. Bath offers an alternative scenario in which each of the seven largest events (from $M_L = 2.6$ to 3.2) is a "main event" followed by its own aftershock sequence. If this is true, the difference between these "main shocks" and their largest aftershocks works out to be an average of $0.5 \pm 0.3 M_L$ units; for earthquakes, this value is much higher (approx. 1.2 to 1.3). Bath interprets the low M_L decrement values as indicators of the brittle nature of the superficial layer, which implies more of a swarm type mechanism. (Rockbursts in Swedish mines do not exceed 3.2 M_L .) The b-values varied significantly over time from $b = 0.27$ to 1.42 to 1.13. (Low b-values indicate higher stress and vice versa. Low b-values may prevail during foreshock sequences or when stresses are related to a loading cycle).

4.6 Ruhr Area, West Germany

Ore: Coal.

Geology: Devonian, sedimentary rocks (Einstein, personal communication)

Mine Depth: Average depth approximately 700 m.

Mining Operation and Area: Not obtained at time of publication.

Monitoring: A 17 geophone network operated in the Ruhr area coal mines for 4 months. During this time a total of 10,000 events registered on the network.

Analysis: Data from the network confirmed that there was a statistical correlation between times of mining and activity.³⁹ There was a typical behavior of the rate of events (increases) as a long wall approached.

Seismograms from the network typically show a weak beginning and stronger vibrations later. Will³⁹ explains this as being a result of the rockbursts occurring within a coal seam. The first onset would be a refracted wave penetrating through the roof or floor material, which has higher seismic velocities than does the seam. Most of the energy would remain in the seam and propagate as channel waves.

4.7 Australia, Sydney Basin, N.S.W., and Bowen Basin, Queensland

Rockbursts are not a widespread problem in Australia, but do occur in the mining areas mentioned. The general problems have been with rockbursts in coal seams and outbursts of gas. (An outburst is the rapid release of absorbed or entrapped gas as a result of rock pressure). In Australia more damage is caused by outbursts than by rockbursts. Therefore monitoring efforts, which include rockburst seismic recordings and standard acoustic monitoring, are aimed toward the prediction of outbursts.⁴⁰

39. Will, M. (1980) Seismoacoustic Activity and Mining Operations, in Proceedings 2nd Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials, Hardy, Jr., H.R. and Leighton, F.W. (Eds.).

40. Grezl, K., Leung, L., and Ahmed, M. (1984) Development of Seismo-Acoustic Monitoring Techniques for Underground Coal Mines in Australia, Proceeding of the Third Conference on Acoustic Emission/Microseismic Activity, in Geologic Structures and Materials, held at Pennsylvania State University, Hardy, H.R. Jr. and Leighton, F.W. (Eds.).

Ore: Coal.

Geology: Not available.

Mine Depth: 500 m (McKavanaugh and Enever⁴¹)

Mining Operation and Area: Not available.

Monitoring: Some monitoring equipment for microtremors has been installed at these mines, which do experience rockbursts.

Analysis: There has been no success in finding precursory phenomena for the prediction of outbursts.

4.8 People's Republic of China

The earliest record of a rockburst in China is in 1933. Since 1949, about 2000 rockbursts have occurred in 32 coal mines. Their largest magnitudes ranged between 2.5 and 3.8 (Richter). Mei and Lu⁴² studied the phenomenon in China for 6 coal mines and 2 metal ore mines. They found that rockbursts in China mostly occur in "hard rock," and increase in number in coal mines with increasing production and depth. They described the typical rockburst in China, and that information is summarized below.

Ore: Coal.

Geology: Hard, intact rock that is highly stressed. Coal seams are usually 0.7 to 10.0 m thick with a variety of dip angles. A typical uniaxial compressive strength is 100 - 200 MPa. The coal usually has a compressive strength of 10 to 50 MPa.

Mine Depth: Depths of mines not available but rockburst depths range from 200 m to 700 m.

Mining Operation and Area: Room and pillar and possibly longwall.

Monitoring: Network information not available. Richter magnitudes range from 1.5 to 3.8. Rockbursts usually occur at 200 m to 700 m and increase in number with depth.

Analysis: The rockbursts are mostly located in coal pillars and advancing stope faces (Type I), through some occur in zones influenced by tectonic moment or local geological anomalies (Type II). Prediction of rockbursts involves a strain energy storage index that uses a load-deformation curve. This technique does not always work because of difficulty estimating the strengths of the material. Complementary to this method, microseismic and acoustic monitoring is used.

4.9 Horonai Coal Mine, Japan

Ore: Coal.

Geology: Not available.

Mine Depth: 1100 m.

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41. McKavanaugh, B.M. and Enever, J.R. (1980) Developing a Microseismic Warning System, in *Proceedings 2nd Conference on Acoustic Emission/Microseismic Activity in Geologic Structures and Materials*, Hardy, Jr., H.R. and Leighton, F.W. (Eds.).
 42. Mei, J., Lu, J. (1987) The Phenomena, Prediction and Control of Rockbursts in China, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpalsal, S. (Eds.), Vol. 2, pp. 1135-1140.

Mining Operation and Area: Mostly longwall mining.

Monitoring: Ten years.

Analysis: Ishijima et al.⁴³ concluded that the seismic energy release rate, used in many areas to predict the potential for causing rockbursts, was more similar to strain energy release rate than to the energy release rate proposed by Cook et al.⁴⁴

4.10 Union of Soviet Socialists Republic

Ore: All ore types considered in this study.

Geology: Igneous, metamorphic, and sedimentary.

Mine Depth: Not available.

Mining Operation and Area: Not available.

Monitoring: Not available.

Analysis: Rockbursts in mineral mines have plagued Soviet mining projects for some time, but the literature is sparse. Markov et al.⁴⁵ attribute rockbursts to dynamic rock pressures that exceed that of simple gravity forces at depth. Statistically they find that this condition occurs 60 percent of the time for projects in igneous rock and 20 percent for sedimentary and metamorphic. In a ten year study, they observe that the probability of rockbursts decreases sharply if the stresses on the opening outline of the mine are reduced even by a small value. A coefficient K_s is defined:

$$K_s = \frac{\sigma_L + \sigma_\theta}{\sigma_{\text{compr}}}$$

where σ_θ is the tangential compressive stress, σ_L is the longitudinal compressive stress, and σ_{compr} is compressive strength of the rock. They state that if $K_s < 0.3$, the probability of rockbursting brittle type failure near the opening is near zero, whereas if $K_s > 0.8$ the probability of rockburst is near 100 percent.

4.11 North Staffordshire Coal Field, England

Ore: Coal.

Geology: Mudstone and shale with intervening coal seams and non-continuous lenticular

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43. Ishijima, Fujii Y. and Sato, K. (1987) Microseismicity Induced By Deep Coal Mining Activity, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpaisal, S. (Eds.), Vol. 2, pp. 987-990.
 44. Cook, N.G.W., Pretorius, J.P.G., Orlepp, W.D., and Salman, M.D.G. (1966) Rock mechanics applied to the study of rockbursts, *J.S. Afr. Inst of Min. Metall.* **66**:435-528.
 45. Markov, G.A., Vorobiev, A.N., and Uralov, V.S. (1987) Geomechanical Criteria of Prediction and Technology of Prevention of Rockbursts During Excavation in Tectonically Stressed Rocks, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpaisal, S. (Eds.), Vol. 2, pp. 101-104.

sandstone bodies.⁴⁶

Mine Depth: 1000 m.

Mining Operation and Area: Longwall.

Monitoring: Seismicity network installed since 1970s. The largest events are approximately $M_L = 3.0$ to 3.5 (Wong,³⁷ Kuszniir⁴⁶). The longwall techniques have triggered the typical pattern of events near the active mine face.

Analysis: The larger events are situated 1 km beneath the surface (at the level of the mine) and have caused damage of up to MMI VI. The larger magnitude events exhibited some shear motion but the smaller ones were mostly implosional.

The frequency-magnitude parameters (a and b) were examined as a function of face advance. These parameters were at their maxima when the active face was under the extracted area of the adjacent seam, and were at their minima when under pillars. The largest events occurred during the minima of the a and b values.

5. TABULATION OF INFORMATION

The information used in Sections 4 and 6 is tabulated in Table 2. This section provides comments that are necessary to understand the table and to know how the information was collected. One has to be aware of the fact that the various reports on different mines from which the material in Table 2 was taken were generally written by different researchers; the information available for each mine is very uneven. For example, some papers written by seismologists would be lacking data on the type of mine or geometry of the mine. Studies by geologists often quote the rate of seismic events but not their magnitude, or they do not include the type magnitude scale used or the detection threshold. Information on the various mines and mining districts has been broken up into general categories in Table 2. When using the table, readers are cautioned that for more than just a general idea of seismic activity and reference material, the original references, or Section 4 should be consulted. A description of the table columns follows:

(1) Mine - the name of the specific mine or mining district used in a seismicity or geological study.

(2) Country - location of mine or district.

(3) Ore - the major mining product.

(4) Geology - in some cases very detailed information on geology and structure is available. In these cases the focus is on the structural properties and the general strength of the rock.

(5) Depth of Mine - if the data are available, this column contains the depth of mining at the time of occurrence of the reported rockbursts. Otherwise it contains an average depth for the mine or mining district.

46. Kuszniir, N.J., Al-Saigh, N.H., and Ashwin, D.P. (1984) Induced Seismicity Generated by Longwall Coal Mining in the North Staffordshire Coal-Field, U.K., Gay, N.C. and Wainwright, E.H. (Eds.), Proceedings of the 1st International Congress on Rockbursts and Seismicity in Mines, Johannesburg, 1982, SAIMM, Johannesburg, 1984.

Table 2. Mine or Mining District Characteristics.

MINE	COUNTRY	ORE	GEOLOGY	DEPTH OF MINE	MINING OPERATION AREA	PERIOD OF COVERAGE	MAGNITUDE FREQUENCY RELATIONSHIP	RATE OF EVENTS	MAXIMUM SIZE OF EVENTS	PRECURSORY PHENOMENA	SOURCE	REFERENCE
Esterhazy Cory	Canada Saskatchewan	potash	soft, most competent layer composed of carbonate	7100 m	Continuous (no blasting)	mostly Canadian regional network since 1960			2.3 to 3.1 magnitude MMI up to V	Prior to 1970, no seismicity		Hasegawa 87 Herget & Macintosh 87 Gendawill 84
Springhill	East Canada	coal	not available	less than 1 km	R & P above 2000 ft. longwall below	no information				Monitoring rise in level of "foreshocks"		Hasegawa 87
Quirke	Elliot Lake, Canada	uranium	dipping, strong brittle quartz high horizontal stress $\sigma_1:\sigma_2=2:1$	500 m	1100 x 600 m room & pillar	Sep 84 to April 85		150 pillar burst type. Previously, in 1982, a large series of events	assume pillar burst - Type I			Udd and Hedley 87
INCO Metal	Sudbury, Ontario, Canada	nickel	low grade disseminated norite		3 mines	instrumented in 1940's				Prior to burst, frequency content of activity increased		Pakalnis 84 Cummins & Given 73
Kirkland	Southern Ontario, Canada		hard rock			no information						Hasegawa 87
General	China	coal	not available	200 - 700 m	32 coal mines in district	since 1949		2000 per 50 years	2.5 to 3.8 assume Type I	using acoustic monitoring		Mei & Lu 87
Chengzi	China	coal	not available		coal pillar recovery	no information			3.4, intensity VII			Hua 87 (Ref. 47)
Heronai	Japan	coal	not available	1,000 m	mostly longwall	10 years				investigate use of strain energy index to predict potential		Ishijima Fujii & Sato 87
Ruhr area	W. Germany	coal	not available	average 700 m	longwall	17 geophone network for 4 months		10,000 events per 4 months	all Type I	rate increased with approach of longwall		Will 80
GDR	Germany	potash	not available			not available			5.4 m_b (Type II)			Stiller et al.
Lubin Copper Basin	Poland	copper		600 - 1000 m		1975-1983	Many relationships derived (see text)	at least 361 events in 10 years	4.0 to 5.0, larger magnitudes possibly Type II	changes in b-value	radii from 70 to 502 m; found M_L to be a direct measurement of seismic moment	Gibowicz 85

47. Hua, A. (1987) Rockburst and Energy Release Rate, in *Proceedings/International Society for Rock Mechanics*, Herget, G. and Vongpaisal, S. (Eds.), Vol. 2, pp. 971-974.

Table 2. Mine or Mining District Characteristics. (Continued)

MINE	COUNTRY	ORE	GEOLOGY	DEPTH OF MINE	MINING OPERATION AREA	PERIOD OF COVERAGE	MAGNITUDE FREQUENCY RELATIONSHIP	RATE OF EVENTS	MAXIMUM SIZE OF EVENTS	PRECURSORY PHENOMENA	SOURCE	REFERENCE
Upper Silesia Coal Basin (Katryna)	Poland Czechoslovakia	coal	2 formations: 1. large number of coal seams, reduced thickness, fine grained sediments. 2. Coarse grained continental sediments (high strength conglomerates)	600 - 1000 m	very high rate of production	since 1982		since 1982, 12 rockbursts and 62 "tremors" recorded	at least one Type II event		events occurring on discontinuities	Konieczny et al.
Witwatersrand	South Africa	gold	hard quartzite	3 km		various arrays	Linear		4 - 5	arrest of tilt displacement	$m_b - M_L$ similar to nuclear explosions	Cook 76
Klerksdorp District	South Africa	gold	extensional, normal faulted hard rock, argillaceous to siliceous quartzites with subordinate conglomerates & shale horizons	average 2.3 km	4 large mines average area = 200 km ²	digital network installed 1986		most smaller than 3.0 mag. More than 6,000 events from mag. 0.2 to 5.4 in ten years	5.2 (Type II) (source radius 84 m, stress-drop = 23 b)		Stress drops similar to earthquakes. Source dimensions larger than Carletonville & ground motion time history more extended	McGarr et al. 87 Gay et al. 84
Carletonville	South Africa	gold	unfaulted, intact rock hard rock	2 - 4 km		digital network installed 1986		May to Oct, 1986 22 mag > 3.5	4.0, upper limit (0.045 G, 376b)		High stress drops, smaller source dimensions, less extended ground motion time histories	McGarr et al. 87
East Rand Proprietary Mine	South Africa	gold	high strength rock	2 - 3 km	300 m longwall & strike pillars	various arrays	b = 0.6	$M_L \geq 2.0$ expected every 12 days	2.8 (Type I) 3.8 (Type II, rockbursts occur in pillars & irregular geometry)			McGarr 82
Blyvoorvuitzicht	South Africa	gold	quartzites, strength 250 MPa	2 - 3 km	4 mines longwall	various arrays since 1978	b = 0.65 to 0.97				source radii from 25 to 65 m stress drop 0.5 to 5 MPa for mag 1.0 to 2.0 FPS showed strike parallel to face, pure shear	McGarr 82 Spittiswoode 84

Table 2. Mine or Mining District Characteristics. (Continued)

MINE	COUNTRY	ORE	GEOLOGY	DEPTH OF MINE	MINING OPERATION AREA	PERIOD OF COVERAGE	MAGNITUDE FREQUENCY RELATIONSHIP	RATE OF EVENTS	MAXIMUM SIZE OF EVENTS	PRECURSORY PHENOMENA	SOURCE	REFERENCE
Grangesberg	Sweden	iron	dipping slab orebody, surrounded by leptyte & granite	500 m		1984 network installed after large event $M_L - 3.2$	inbetween swarms & aftershocks. For $1.1 \leq M_L < 3.2$, $\log R = 3.04 - 1.08 M_L$ here is larger than for natural crustal earthquakes ($b = 0.85$)	1000 events in less than 4 years recorded after main shock	$M_L = 3.2$		focal mechanism for large event showed shear failure not cavity collapse	Bath 84
Sunnyside coal mining district	Eastern Utah USA	coal	4 m thick coal seam, underlain by thick-strong thick bedded sandstone 24-40 in. thick. Overlain by weak 45 m thick shale & sandstone	events cluster at 1 km ranged from 1 to 3 km depth	room & pillar	microearthquake study undertaken		from 1967 through 1970: 50,000, 20,000, 27,000 and 1500 seismic events per year. 1,700 > 1.5 magnitude	range from -1.0 to 2.8 mag unit. The larger magnitude occurred away from immediate mine on pre-existing faults		composite fault plane solution shows thrusting. Corner frequencies from 10 to 14 Hz. Strike of FPS agrees with tectonic stress field	Smith et al 74 Wong 85
Book Cliffs-E. Wasatch Plateau	Utah, USA	coal	numerous and complex joints and faults			regional network		very high natural induced (Type I) seismicity. Densest clusters of activity where mining exceeds 50,000 tons	$M_L 4.0$		Type II's occurring on deep faults, FPA agree with horizontal tectonic stressfield studies	Wong 85
Coeur d'Alene mining district (general)	Northern Idaho, USA	metals	intensely faulted sheared structural knot Precambrian rock ranges from fine-grained argillites & siltites to coarse grained quartzites			no information on seismic arrays						Wallace & Morris 86

Table 2. Mine or Mining District Characteristics. (Continued)

MINE	COUNTRY	ORE	GEOLOGY	DEPTH OF MINE	MINING OPERATION AREA	PERIOD OF COVERAGE	MAGNITUDE FREQUENCY RELATIONSHIP	RATE OF EVENTS	MAXIMUM SIZE OF EVENTS	PRECURSORY PHENOMENA	SOURCE	REFERENCE
Star	Northern Idaho, USA	lead zinc silver	see "Coeur d'Alene", above. Hard brittle rock, high horizontal stresses	7900 ft	horizontal timbered cut and fill method. Produce 1,000 tons of ore per day. Complicated geometry	24 geophone network installed 1975					activity associated with quartzite band that traverses center of main vein ore body at sharp angle	Langstaff 80
Central Pennsylvania	USA	coal	not available	600 ft	longwall blasting	geophone array		microactivity strongly proportional to daily mining schedule. Activity remains high for 5 min. after blast	Type I		Depth of event within 100 ft of coal seam	Hardy & Mowry 76
Sydney Basin Bowen Basin	N. S. W. Queensland Australia	coal	not available	500 m		some monitoring equipment for micro-tremors installed			mostly outbursts are of concern	Inconclusive		McKavanaugh & Enever 80 Grazi et al. 84
Staffordshire	Great Britain	coal	mudstone and shale with intervening coal seams & non-continuous lenticular sandstone bodies	1 km	longwall	seismicity network since 1970's	a & b parameters affected by position of advancing face (See text, Sec. 4.11)	Type I only	M ₁ 3.0 - 3.5 Type I Largest events occur when advancing face under pillars	Largest events occurred during smallest a and b values		Wong 85 Kusznir et al. 84

(6) Mining Operation and Area - this is a very general column that identifies where possible (1) the type of mining technique in use during the study period, (2) very approximate dimensions of the mine (which may or may not be concurrent with the reported seismicity), and (3) where published, the excavation rate at the time of the study or an average figure over the lifetime of the mine.

(7) Period of Coverage - this is usually the time during which the seismicity reported in the "Rate of Events" column occurred. The specific mine may have had arrays of geophones installed for a longer period or discontinuous periods.

(8) Magnitude Frequency Relationship - any comments regarding the $\log N = a - bM$ curve are included here.

(9) Rate of Events - basically any statistic on the occurrence of rockbursts with an associated time period is included here. This entry cannot be used for recurrence calculations because (1) often no detection threshold or saturation cutoff for the monitoring network is listed, (2) the areal extent of coverage for completeness and density calculations is not included, (3) often the size of the event is not mentioned.

(10) Maximum Size of Event - in this column an attempt to differentiate Type II rockbursts from Type I rockbursts is made. In most cases the maximum reported event is for the "period of coverage" only, whereas in other cases it is the largest known event to have ever occurred in the mine or to be associated with the mining.

(11) Precursory Phenomena - any techniques in use at the mines for prediction purposes, whether successful or not, are listed here.

(12) Source - this column lumps information on spectra, magnitude ratios, stress drops, duration, etc. into one section. Since very different information is computed at the different locations, space limitations prevent a narrower breakdown.

(13) Reference - all of the specific tabulated data can be found in the listed references.

This table is offered only as a shorthand summary and should be used only in conjunction with the detailed mine profiles presented in Section 4.

6. DISCUSSION AND CONCLUSIONS

In this study, rockbursts have been divided into two categories, Type I and Type II. Table 1 reviewed some of their distinguishing properties. This is a gross simplification, but is necessary since the published studies often do not distinguish between the mechanisms. While Type II rockbursts are defined as those involving fault slippage along preexisting faults, all other rockbursts have been lumped into the Type I category. Most Type I rockbursts are directly related to the mining operation and occur within tens of meters of the advancing mine wall. The rest consist of other mechanisms as suggested in Section 3.6, Figure 9.

There are several factors that are almost certainly involved in the inducement of Type I and Type II rockbursts. Table 3 presents a summary of the factors that are involved in determining the magnitude-frequency relationship (Equation 1), upper limit magnitude, stress drop, and location of both types of rockbursts.

Table 3. Factors that Affect Rockburst Characteristics

	Log N = a - bM		Upper Limit Magnitude	Stress Drop	Location	
	a	b			Epicenter	Depth
TYPE I	Excavation rate; characteristics of blasting operation	local stress field	nature of rock (geology, intact or faulted)	nature of rock (hardness properties)	distance from advancing mine face	geology of strata (layering, weak zones)
TYPE II	areal extent of mine; geometry plate tectonic forces, alignment of pre-existing fault with induced stress field	regional stress field	size of preexisting fault plane; magnitude of mining induced stress redistribution; presence of regional tectonic stress field; nature of fault surface (crunchy, smooth) dimensions of mining operation	nature of fault surface	within the area of stress perturbation resulting from mine or mine district	location of fault

The magnitude-frequency relationships of Type I events are particularly affected by the mining operations, excavation rate, and blasting schedule. The upper limit magnitudes are a function of the strength of the rock. The epicenter locations are a function of the mine location and geometry. Depths of Type I events seems to be controlled by the location of geologic strata of differing strength.

There have not been enough Type II rockbursts in any one region to construct a magnitude-frequency curve. However, the magnitude-frequency statistics probably depend on the areal extent and shape of the mine, and on the alignment of plate tectonic forces relative to preexisting faults and to the mining-induced stressfield. The upper limit magnitude of a Type II rockburst is not well constrained but must be a function of preexisting fault plane geometry in relation to the mining-induced stressfield, possibly coupled with the regional tectonic stressfield. The locations of Type II rockbursts must fall within the area of stress perturbation caused by the mine or mining district, and depend on the location of a fault plane surface.

Although rockbursts occur in many areas that are engaged in active mining, very few areas have been the subject of sophisticated studies that result in the production of fault plane solutions, earthquake moments, stress drops, or other kinds of spectral analysis. Indeed, many studies on the phenomenon do not include even the barest minimum of coincidental information that would facilitate the comparison of one mine to another. This missing information includes parameters such as mine geometry, magnitude detection cut-off of the monitoring network (to determine the range for completeness for rates of events), type of magnitude scale used, maximum size event during period of coverage, and excavation rate during the study period. Without this information, especially the average excavation rate, it is impossible to compare the level of activity in one mine with another. The recent surge in mining and the interest in rockburst problems should alleviate this problem through increased communication between investigators and heightened awareness of the need for a general understanding of the problem.

Despite these limitations, several trends were apparent in the data available on the 25 mines or mining districts. It should be noted that, understandably, no reports were found describing the conditions at mines that have *not* experienced a rockburst problem. For completeness, a study should include data on such mines as experimental controls.

6.1 Observations

Observations from this study can be classified into four types: (1) factors or characteristics that can definitely be identified with mining induced seismicity on a worldwide basis, (2) factors that have been suspected of being related but the relationship is not well supported, (3) questionable relationships, and (4) questions that are basically open because of lack of investigation or lack of data.

6.1.1 FACTORS CORRELATED WITH MINING INDUCED SEISMICITY

Four factors can definitely be identified with mining induced seismicity on a worldwide level:

(1) There is no doubt that the number of Type I rockbursts can be expected to be, for the most part, a direct function of the excavation rate. This has shown to be true in any of the mines that have data on mining rates. For example, in South African mines, Type I rockbursts decrease by a factor of 3 from Saturday (full working schedule) to Sunday (no mining) (McGarr, personal communication).

(2) Locations (hypocenters) of Type I rockbursts consistently are determined by the location of the mine face and by local geological structure. The rockburst epicenters are most often within a few hundred feet ahead on an advancing face. The depths can be above or below the level of the active mine excavation. The presence of stratified layers of differing geologic and rock mechanical qualities can concentrate the rockburst foci at a discrete depth interval. If structural discontinuities in the rock exist (fractures, faults, or other zones of weakness) rockburst hypocenters may migrate to these structures.

(3) The following generalizations are based mostly on evidence from South African gold mines (the work of McGarr) in hard rock areas: (a) When breakage occurs along preexisting faults, higher magnitudes and lower stress drops and ground motion parameters (similar to natural earthquakes) result. (b) By contrast, when there is breakage of intact rock, as sometimes occurs ahead of an advancing stope face, upper limit magnitudes are often lower than in case (a) (because of smaller fault area) and stress drops are high (relative to natural crustal earthquakes with the same magnitude and source radius).

(4) It is possible that a preexisting fault can be made to have a Type II rockburst by the presence of an extensive mining system even though the fault was "inactive" prior to the existence of the mine. South Africa provides a good example. In August of 1987 a mining strike occurred during which production halted for 3 weeks. During this time a drop in a -value of about 2 (preliminary estimate, McGarr personal communication) was observed in the magnitude frequency relationship:

$$\log N = a - bM.$$

This translated into a factor of 100 in reduced seismicity. With resumption of mining the seismicity returned to the former high level. This amplification of seismicity might occur for the Type II rockbursts also. An increase in activity by a factor of 100 could turn the extrapolated recurrence rate

of a major event into a considerable seismic hazard problem. For example, critical facilities such as nuclear power plants in the United States are designed to the 1 in 10,000 year event. If the presence of an extensive mining district can change a 1 in 1,000,000 year event to a 1 in 10,000 year event, this would have serious consequences for planning in the region. The point is that an extensive mining district may create an earthquake hazard in areas where virtually no seismicity is evident prior to mining.

6.1.2 FACTORS SUSPECTED BUT NOT WELL SUPPORTED

Researchers have theorized that several factors might correlate with mining induced seismicity, but the author has found that these theories are not supported by worldwide data.

(1) Many researchers have monitored various phenomena in search of precursory indicators, but no consistently reliable methods have been found. Acoustic emission monitoring is in extensive use, but although the information is valuable for other purposes, it has not reliably predicted large rockbursts. This is probably because the causative mechanism for microfracturing is only indirectly related to that for rockbursts. There are some isolated cases of success in predicting rockbursts, but the methods require further study: (a) One histogram of events in Canada seemed to indicate a rise in the level of the number of smaller shocks prior to a very large rockburst sequence. (b) In Poland some of the larger events occurred during low b-value intervals. (c) Arrest of tilt was observed before a large rockburst in South Africa. (d) Stopinski and Dmowska have had success predicting rockbursts with electrical resistivity methods in Poland.

(2) Some studies imply that the maximum size of rockbursts increases with the depth of the mine, but these studies do not include specific investigation, and the assumption is not supported by this survey of worldwide data. In fact, it has been shown in some areas, specifically South Africa, that in deep mines depth is not a strong factor in limiting the maximum magnitude events (that is, there is little difference between 1 km and 3 km in maximum size of rockbursts). The maximum size Type I rockburst for a given area is clearly controlled by a combination of factors.

6.1.3 QUESTIONABLE RELATIONSHIPS

It is difficult to separate the influence of the geology and the natural stressfield from the influence of the mine, especially in areas where there has been no natural seismicity. There are two major questions:

(1) The question of whether the upper limit magnitude of Type I rockbursts increases with excavation rate is impossible to answer at this time. This is because the rockburst studies do not generally include concurrent excavation rates. When the excavation rate in a mine increases, one of two scenarios will result. In the first scenario, the a-value in the frequency-magnitude relationship increases, but the b-value stays the same. In this case the ratio of large to small shocks stays the same. In the second scenario, the a-value increases but the b-value decreases. (Cook⁷ predicts that the b-value will decrease with increased energy release rate; an elevation in stress state will also cause a decrease in b-value). In this case the ratio of large events to small events increases.

Even though the ratio of large to small events may change, the maximum size event should remain constant, as a function of the strength of the rock. This is because the geological and rock mechanical properties are not changed by mining (except in the case of a change in the availability of

water). This suggestion is consistent with the observations. Even those mines with the highest activity rates do not experience Type I events greater than about 4.5 magnitude. The magnitude-frequency curves for mines with similar geology but different activity rates might look like the curves in Figure 14. (The amplitude of the cavity collapse component of a rockburst may be increased with mine volume, although this mechanism accounts for less than 15 percent of the energy in rockbursts).

If the maximum size of Type I rockbursts is a function of local geology, it appears from this study that Type I events in shallow to average depth, soft to medium hard rock mines have the potential to range from 2.8 to about 3.8. Deep, hard rock mines in old cratonic shields have the potential for maximum magnitudes from 3.8 to 4.8. Larger magnitudes rockbursts in these areas are probably Type II events.

(2) The relationship of rockburst orientation to the stressfield is hampered by the sparsity of fault plane solutions for different tectonic/geologic areas, even though this study contains information on rockbursts that have occurred in stable cratonic shield areas (Africa, Canada) and seismically active areas (Utah, Japan).

In both types of areas, stress measurements have shown that there can be erratic variations of stress direction and magnitude with depth near mines. These variations are probably caused by the geometry of the mine coupled with local geological discontinuities, or may be remnant stresses locked in from ancient tectonic orogenies, especially in old shield areas.

In summary, stresses in the upper crust cannot be assumed to be the result of pure gravitational loading or of the broad tectonic regime.

For Type I rockbursts, the stress concentration caused by the mining geometry probably has a major effect on the orientation of the fractures. For Type II rockbursts the orientation of the fault plane is constrained by the preexisting faults in the area. How the local stressfield of the mine couples with the preexisting regional stressfield to cause Type II rockbursts is unknown. It is also unknown whether the presence of the tectonic stress field that originally formed the fault is necessary for the mine to trigger movement on the fault.

6.1.4 OPEN QUESTIONS

At least three areas remain open and await further research.

(1) The reason that in some areas the pattern of rockbursts more closely resembles that of earthquake aftershocks, but in other areas resembles swarms, is undetermined from this study. There were too few studies that looked at the distribution of rockbursts to make any correlations with geology, depth of mine, or other factors. The author speculates that it is a function of the amount of faulting in the rock and the external stresses on the mining area. (Intact rock would yield results more similar to aftershock sequences because of the change of initial conditions after rupture.)

(2) After a cessation of mining, the number of rockbursts (mostly Type I) decreases. The decay time varies from almost instantaneous, about 1 day (for the hard rock gold mines of South Africa), to much longer, even up to a year (for the coal mines of Poland and Czechoslovakia). The decay times are probably controlled by the stressfield and by the local structure and geology. But there have been no investigations into decay times.

(3) The relationship of the size of Type II rockbursts to the dimensions of the mining district has not been established. There is speculation that the maximum length of the fault involved in rupture is

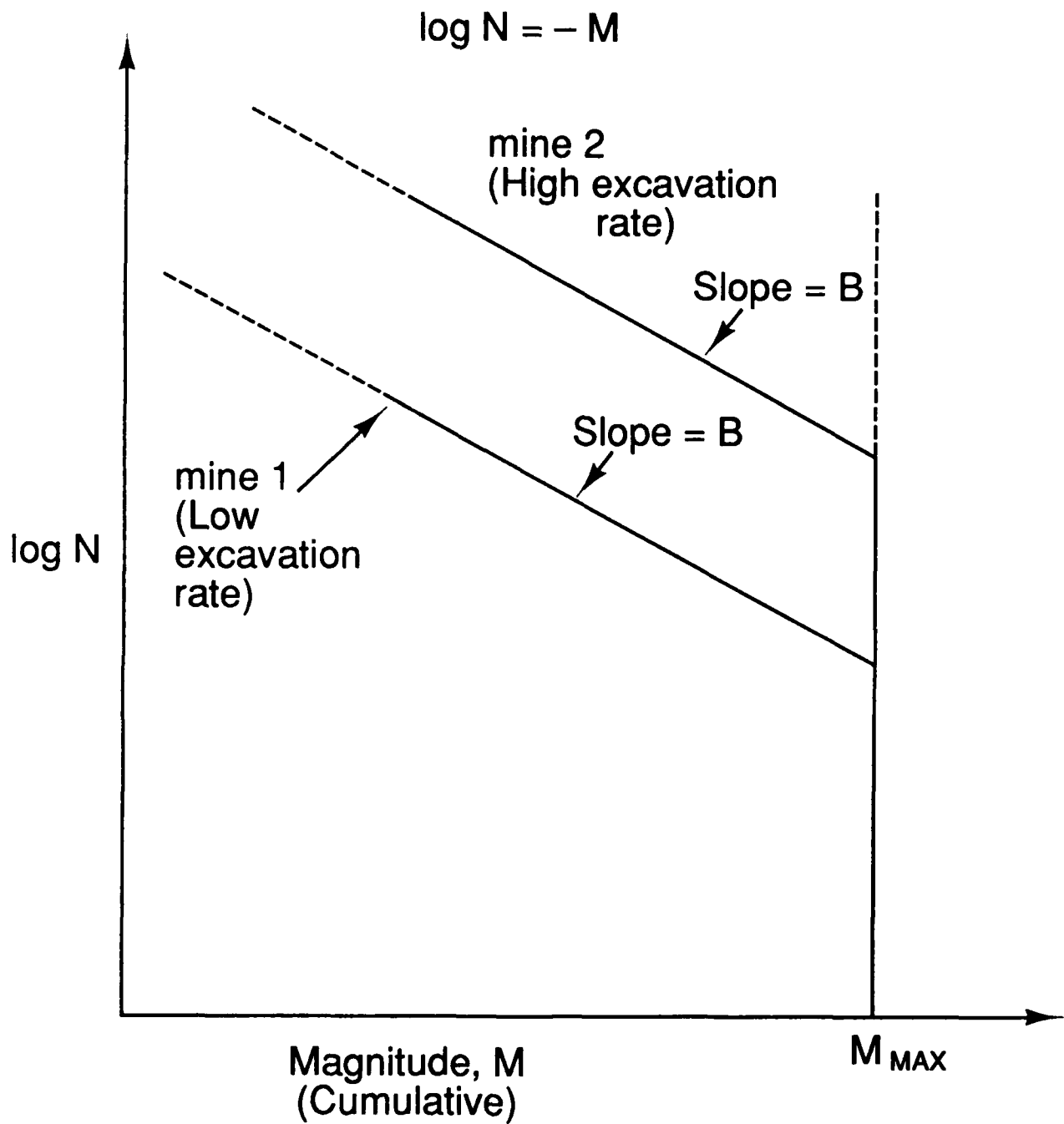


Figure 14. Theoretical magnitude-frequency curves for mines with similar geology but different activity rates. Although a-value changes, theoretical maximum size event is unchanged.

controlled by the largest mine dimension. The question becomes particularly important in regions where there are many mines, where even larger fault areas might be triggered. This study cannot place an upper limit to the size of Type II rockbursts on the basis of available data.

6.1.5 RECOMMENDATIONS

The phenomenon of rockbursts is only beginning to generate coordinated international attention. The field is wide open for further study. Many techniques that are used to study earthquakes could also be used for rockbursts.

From this study, several areas emerge that are particularly in need of further research. These are listed below along with a suggested list of information to be included in any rockburst seismicity reports.

(1) More study of Type II events is needed, particularly on the magnitude-frequency relationship. Type II events should not be included with Type I events on the same magnitude-frequency curve because of the different causative mechanisms involved. Separating data for Type I and Type II events, although difficult, would be valuable for extrapolating recurrence rates of large events. Whenever a mining development is being put in place or reactivated, the potential for inducing Type II large events must be given serious consideration. The largest identified Type II rockbursts for this study range from high 4's to 5's. It is possible that some larger events have been triggered by mining but have been classified incorrectly. South Africa might be the area for which the most data on Type II events can be separated from data on Type I events.

(2) Some mines do not experience rockbursts. If some of these mines are in close proximity to ones that do have rockbursts this would provide a useful experimental control over factors that cause rockbursts. Where possible, descriptions of these seismically quiet mines should be included in any rockburst study.

(3) A comparison of characteristics of rockbursts for Canada and South Africa would be particularly useful. Although both these areas are tectonically stable and have very deep mines, they differ greatly in stress ratios (Canada $\sigma_h > \sigma_v$ South Africa $\sigma_h < \sigma_v$).

(4) Monitoring efforts provide valuable data even though they have been largely unsuccessful at predicting large rockbursts. Newer methods, such as electrical resistivity techniques, should be tried, and used in conjunction with other indicators such as elevated acoustic emission levels, hardness tests, etc.

(5) To facilitate comparisons of one rockburst prone area to another, certain standard information should be included in reports. The author suggests the following checklist:

Statistics on mining operation:

- type of ore
- type of mining operation
- dimensions of mine (with dates)
- rate of excavation

Geological information:

- rock type, including mechanical properties
- structural geology, including fractures, bedding,
and faults, as well as type of faulting

estimates of stress in crust

Seismic monitoring:

period of coverage

detection threshold magnitude

Seismic activity:

pre-mine seismicity

epicenter map (to help distinguish Type I from Type II rockbursts)

spectra (where possible)

Magnitude scale:

clearly defined

if nonstandard, include magnitudes for a few events that have been
recorded on regional networks (for scaling purposes)

fault plane solutions

6.2 Concluding Remarks

This study has shown that there are many kinds of rockbursts. There are those whose frequency as a function of mining activity is fairly well understood. These are the majority of the Type I events. Some Type II events, which are caused by modification of stress fields so that slippage occurs on a preexisting fault are at least conceptually understood. In between these two is a wide range of phenomena awaiting rigorous study.

Rockbursts are in some ways similar to natural earthquakes and in some ways different. However, because of their frequency and potential for very tight array coverage, rockbursts afford an opportunity to better understand the earthquake rupture process. Like earthquakes, it appears that prediction of rockbursts must rely on an optimization of a combination of indicators such as acoustic emissions, electrical resistivity techniques, b-value changes, and hardness tests.

Rockbursts differ from earthquakes by having some non-shear energy in their spectra. This also offers a unique opportunity to study source models and discrimination techniques.

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